Modelling erosion in complex geometries

22nd May 2019, Bjerringbro, Denmark
• Background
• Erosion
• Modelling erosion
  • Fluid erosion
  • Particle erosion
• Case studies
  • Vertical roller mill
  • The Jet Impingement Test
  • Centrifugal slurry pump
• Some conclusions & Future work
Background
• Masters in Mechanical Engineering – University of the Basque Country
  UPV/EHU (Bilbao, Spain)

• Head of Services – Asaser S.A. (Bilbao, Spain)

• PhD in Mechanical and Aerospace Engineering – University of Strathclyde
  (Glasgow, UK)

• Research Fellow (School of Chemical and Process Engineering) – Discrete
  Element Modelling and CFD-DEM, Additive Manufacturing, Breakage and
  Powder flow

• Lecturer (Fluid Mechanics, Machine Design, Thermodynamics...) –
  University of Deusto (Bilbao, Spain)
Erosion

- Very complex process influenced by many different variables

<table>
<thead>
<tr>
<th>For particles</th>
<th>For surfaces</th>
<th>For the carrier fluid</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Impact and rebound angles</td>
<td>1 Physical properties</td>
<td>1 State of motion (laminar versus turbulent)</td>
</tr>
<tr>
<td>2 Impact and rebound speeds</td>
<td>2 Change in shape caused by erosion</td>
<td>2 Velocity</td>
</tr>
<tr>
<td>3 Rotation before and after impact</td>
<td>3 Stress level</td>
<td>3 Temperature</td>
</tr>
<tr>
<td>4 Shape and size</td>
<td>4 Temperature</td>
<td>4 Chemical composition and physical properties</td>
</tr>
<tr>
<td>5 Volume concentration and surface flux</td>
<td>5 Presence of oxide (or other) coatings</td>
<td></td>
</tr>
<tr>
<td>6 Physical properties (hardness strength and density)</td>
<td>6 Simultaneous occurrence of corrosion</td>
<td></td>
</tr>
<tr>
<td>7 Fragmentation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 Interactions (with surfaces, fluid or other particles)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9 Temperature</td>
<td></td>
<td></td>
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<tr>
<td>10 Presence of additives</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11 Electrical charge</td>
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</tbody>
</table>

Table 1: Factors affecting erosion (1)

- Also related to corrosion processes
- Simultaneous occurrence – higher material removal expected

\[
S = T - (E + C)
\]

- S = Synergy (Additional wear rate experienced by the material)
- T = Total wear rate
- E = Pure erosion wear rate
- C = Pure corrosion wear rate

- Visiting Scholar at Strathclyde University collaborating on Erosion-Corrosion modelling
Erosion

- Main expression used in erosion prediction:
  \[\text{wear rate} \propto V^n\]
- Exponent varies depending on author and experimental methodology

<table>
<thead>
<tr>
<th>Target Material</th>
<th>Erosion particles</th>
<th>Exponent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soda-lime-silica glass</td>
<td>SiC, 120 gritt</td>
<td>3.0</td>
</tr>
<tr>
<td>MgO (96.5%)</td>
<td>SiC, 120 gritt</td>
<td>2.7</td>
</tr>
<tr>
<td>Al₂O₃ (99.5%)</td>
<td>SiC, 120 gritt</td>
<td>2.7</td>
</tr>
<tr>
<td>Pyrex glass</td>
<td>Al₂O₃ 30µm to 10µm</td>
<td>2.2 2.7</td>
</tr>
<tr>
<td>Hot pressed Si₃N₄</td>
<td>SiC 8µm to 940µm</td>
<td>4.0</td>
</tr>
<tr>
<td>Silicon</td>
<td>Al₂O₃ 23µm to 270µm</td>
<td>3.4 to 2.6 depending on particle size</td>
</tr>
<tr>
<td>Reaction bonded SiC</td>
<td>Al₂O₃ 130µm to 270µm</td>
<td>2.3 to 2.0</td>
</tr>
<tr>
<td>Hot pressed SiC (96.5%)</td>
<td>Al₂O₃ 130µm to 270µm</td>
<td>1.8 1.5</td>
</tr>
</tbody>
</table>

Table 2: Velocity exponent for erosion data: normal incidence (2)

\[\text{wear rate} = K V^a D^b\]

Table 3: Review of particle diameter and velocity exponents as shown(3)

Influence of particle rotation

Figure 1: Influence of rotation on weight loss – angle relation. The assumed distribution for the dimensionless parameter \(a = \frac{\phi_0 \cdot U}{V}\) is also shown, where \(\phi_0\) is the rotational velocity, \(U\) is the particle velocity and \(r\) is the particle radius(4)
Erosion

- **Particle concentration**
  - Erosion rate increases with particle concentration – more impacts
  - Concentration effects on erosion rate also depend on particle shape
  - Erosion rate decreases with increasing angle of impingement in all cases

- At high concentrations - particle collisions seem to decrease erosion rate

- More than 2000 different erosion models (6)
- Two mechanisms
  - Cutting wear
  - Deformation Wear

Figure 2: Effect of an increase in particle concentration on different alloys (5)

Figure 3: Example of Cutting ($W_C$) and Deformation ($W_D$) Wear contributions (6)
Modelling erosion
Modelling erosion

**Fluid erosion (7-9)**
- Purely fluid-mechanical erosion
- Especially recurrent in natural processes
- Erodible bodies moving in viscous fluids
- Studies of the erosion of a clay cylinder in flowing water
- The wedgelike front forms by about 45 min and then persists

**The boundary retreats with a normal velocity:**

\[ V_n = -C|\tau| \]

Figure 4: Flow around cylindrical body: Left t=5 mins; Right, t=55 mins (7)

Figure 5: Evolution of an erodible body (clay) in a 61 cm/s flow. Extracted interfaces every 5 minutes. (8)
Modelling erosion

- **Particle erosion**
  - **Particles inside a fluid**
    - Eulerian-Eulerian
    - Eulerian-Lagrangian
      - Single particles
      - Computational parcels
  - **Euler-Euler**
    - Water and Particles both treated as continuous phases
    - Large particle concentrations
    - Particle-Particle interactions and influence of the particles on the continuous phase are important
  - **Euler-Lagrange**
    - Continuum equations solved for the fluid phase
    - Newton’s equations for motion solved for the discrete phase

- **Coupling possibilities**
  - **One-way-coupling**
    - Fluid -> Particles
  - **Two-way-Coupling**
    - Fluid <-> Particles
  - **Four-way-Coupling**
    - Fluid <-> Particles + Particle Collisions

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Figure 6: Graphical representation of the forces acting on the particles and Newton’s equations
• Criteria for choosing the transport model (10)
  • Particle mass loading

\[
\beta = \frac{\text{particulate mass per unit volume of flow}}{\text{fluid mass per unit volume of flow}} = \frac{\rho_p r_p}{\rho_f r_f}
\]

\( r = \) Volume fraction, \( \rho = \) Density and subscripts p and f refer to particle and fluid phases respectively.

• Significant two-way coupling is expected when \( \beta > 0.2 \)

• Stokes number

\[
S_t = \frac{\rho_p D_p^2 V_s}{18 \mu_f L_s}
\]

• \( S_t > 2:0 \) the particulate flow is highly inertial (confined geometry - dominated by particle-wall interactions).

• \( S_t < 0:25 \), particle-wall interactions negligible. If \( S_t < 0:05 \) particles follow the fluid flow.

• Particle shape modelling

• CFD
  • Roundness factor (0-1)
  • Ratio involving particle perimeter and projected area

\[
R = \frac{P^2}{4\pi A}
\]

• Particle shape modelling

• DEM
  • Clumped spheres
  • Polygonal shapes

Figure 7: Polygonal particle break-up and approximation of particle shape with clumped spheres method
Case Studies
Modelling erosion

The Jet impingement test

- **Setup**
  - **Euler-Lagrange simulation**
  - Particles impinging on a flat plate
  - One way coupling - Particles have no effect on the fluid phase
  - Drag force
  - No gravity
  - Stochastic dispersion
  - Surface injection
  - Particle variables are gathered as they impact the target Surface
  - `postPatch` function in OpenFOAM
  - Built-in or UDF in Ansys Fluent
  - Erosion field - Values at the boundary faces
Modelling erosion

• **Ansys Fluent OpenFOAM**

  ![Comparison of eulerian phase: Ansys Fluent 14 (Left), OpenFOAM (Right)](image)

  Figure 9: Comparison of eulerian phase: Ansys Fluent 14 (Left), OpenFOAM (Right)

  ![Target subdivisions (Left), Ansys Fluent 14 Vs Ansys Fluent 15 Impingement velocity-Target radius](image)

  Figure 10: Target subdivisions (Left), Ansys Fluent 14 Vs Ansys Fluent 15 Impingement velocity-Target radius

• **Solver verified against Ansys Fluent 15**

  ![Full domain with simulated particles coloured by velocity and target (Left); OpenFOAM 2.2.x Vs Ansys Fluent 15 Impingement velocity-Target radius (Right)](image)

  Figure 11: Full domain with simulated particles coloured by velocity and target (Left); OpenFOAM 2.2.x Vs Ansys Fluent 15 Impingement velocity-Target radius (Right)
Modelling erosion

- Wear-dependent flow conditions
  - Erosion produces deformation of the surface, which in turn, induces flow changes
  - Variables change (particle impact angles, velocities)
  - New stagnation points appear as shown in Nguyen et al. (10)

Figure 12: New stagnation point after 30 min erosion (Left); Evolution of velocity profile with erosion at different times (Right)
Modelling erosion

- **Geometry deformation**
  - Interpolate values of the erosion field at the face centres
  - Surface Normal Vectors
  - Deform mesh by writing new “pointMesh”
  - Refine mesh where it’s been deformed

![Figure 14: 3D Example of interpolation of values on target’s faces](image1)

![Figure 15: 3D geometry before and after JIT](image2)

![Figure 16: Illustration of surface normal vectors](image3)

![Figure 17: Erosion in pipe and deformed surface](image4)
Modelling erosion

• Validation

Comparison of 3D scanned wear scars (10) and computational wear scars for the Jet Impingement test

Figure 18: Profile of the wear scar along the radius, pressure and velocity fields before and after being eroded

Stagnation point detected for a scar depth 1.8 times smaller than that the one reported by Nguyen et al. (11).
• Validation

• Velocity and pressure fields ≈ constant until deformation is large enough to affect flow field

• Scaling factors applied - Progressively larger deformation

• Deformation step – After appearance of stagnation point

Figure 19: Geometry and pressure field (Pa) of eroded target for different scaling factors
Modelling erosion

- **Erosion-time dependency**
  - Solve Fluid Flow
  - Calculate Erosion Field
    - Introduce particles
    - Calculate trajectories
    - Compute erosion Field
  - Deform Mesh

- **Stepwise deformation**
  - Calculate impact averages
  - Scale-up erosion
  - Deform mesh
  - Remesh
  - Recalculate fluid flow

- **Laplacian solver**
  - DPMFoam
  - Dynamic Mesh Laplacian solver
  - Dictionary with erosion parameters
  - Fluid flow solution dependent on erosion field

Figure 20: Illustration of erosion solver loop (Left); videos of mesh deformation and its effect on fluid flow (Right)
Erosion

• The Vertical Roller Mill
  • Eulerian phase modelling
  • Analysis of air flow
  • Very complex geometry
  • Ansys Fluent

Figure 26: Vertical roller mill examples: Particle trajectories (Top-left), Erosion and Geometrical configuration (Right)
Modelling erosion

- Centrifugal slurry pump
  - Eulerian phase modelling
  - Steady state & Transient simulation
  - Erosion field proportional to $V^2$ close to the boundary for the volute
  - Apply mesh deformation

Figure 27: Erosion on centrifugal slurry pump’s volute

Figure 28: Centrifugal slurry pump transient simulation
Modelling erosion

- **Centrifugal slurry pump**
  - Compared results to *volute* eroded in the field
  - Very similar erosion pattern
  - With deformed geometry – possible to obtain performance decay with erosion progression
  - Calculate erosion – Deform mesh- Recalculate performance
  - Possible to create holes in mesh to simulate extreme erosion cases
  - Impellers with partially missing blades

Figure 29: Centrifugal slurry pump eroded volute compared to real eroded volutes
Modelling erosion

- Centrifugal slurry pump
- Impeller erosion approximation
- Averaged fields for the transient simulation
- Unknown conditions for slurry and position of pump

Figure 29: Centrifugal slurry pump eroded impeller compared to real eroded volutes
Future work
• **Accuracy** of deformed domain increases with decreasing mesh size
• Application of the deformation algorithm is limited when - after application - boundaries intersect due to excessive deformation
  • Alternatives to deal with intersecting geometries – Holes in geometry
• Mesh deformation algorithm is independent of the geometrical configuration
• Ability to predict fluid flow changes with erosion – Implemented erosion solver with a Laplacian Solver for the re-meshing
• Deformation algorithm valid for other processes such as **fouling**, scouring erosion, progressive blockage etc – Inverted surface normal
• Coupling of the deformation algorithm to other fields such as pressure to simulate other processes
• Affect **boundary** with material **inhomogeneity** – Casting
• Predict **most vulnerable erosion spots**
Future work

- Gnanavelu et al. (13,14)
  - Jet Impingement Test
  - Wide range of impact angles and velocities
  - Monitor impingement conditions
  - Velocity and Impact angle
  - Obtain erosion equation
  - Wear Map
- **Three dimensional implementation of the Wear Map Method**

- Strathclyde University – Ongoing collaboration on CFD modelling on Erosion-Corrosion processes
- University of Deusto - Additive manufacturing – DEM and experiments – Beatriz Achiaga


Thank you!
Questions?