Precise prediction of NNS HIP components through DEM and FEM modelling

Yuanbin Deng, Anke Kaletsch, Alexander Bezold, Christoph Broeckmann

*Institute for Materials Applications in Mechanical Engineering (IWM), RWTH Aachen University

HIP17 - 12th International conference on Hot Isostatic Pressing
Sydney Australia, 08.Dec.2017
Content

Introduction
- Purpose of the study
- Process description

Simulation of HIP Process with “Image Analyzed” Densities Distribution
- “Image Analyze” for investigation of initial density distribution
- FEM Simulation

Simulation of HIP Process with DEM simulated Densities Distribution
- Introduction of DEM and Modelling Approach
- Validation, Simulation and Comparison

Summary and Outlook
Purpose of the study

- Anisotropic shrinkage of capsule during PM HIP:
  - Inhomogeneous powder densities distribution in the capsule
  - Temperature gradients and inhomogeneity in the HIP Unit
  - Imperfection of material

Welded Capsule (SS304) filled with powder (SS316L) before HIP Process

Capsule (SS304) filled with powder (SS316L) consolidated to full dense after HIP Process

\[ T_{HIP} = 1125^\circ C \]
\[ P_{HIP} = 110 \text{ MPa} \]
\[ t_{Holding} = 2 \text{ h} \]
Process description

- Trial and error
- “Image Analyze” for Investigation of initial density distribution
- FEM-Simulation of HIP Process

HIP process in general: (a) Capsule production; (b) Filling powder, tapping and vibration; (c) Evacuation; (d) Sealing capsule; (e) Applying high temperature and high pressure; (f) Full density HIPed component
Content

Introduction
- Purpose of the study
- Process description

Simulation of HIP Process with “Image Analyzed” Densities Distribution
- “Image Analyze” for investigation of initial density distribution
- FEM Simulation

Simulation of HIP Process with DEM simulated Densities Distribution
- Introduction of DEM and Modelling Approach
- Validation, Simulation and Comparison

Summary and Outlook
Relative Density (RD) of each window = \frac{\text{Amount of powder}}{\text{Total area of the window}}
FEM densification model

ABAQUS

Get initial Values:
\( \sigma_{ij}, \Delta \varepsilon_{ij}, T, t, \Delta t \)
\( \rho, \rho_0, \sigma_0, r_1, f_1, \varepsilon_{ij}^{\text{inel}}, \varepsilon \)

Calculate:
\( E, \nu, C_{\text{el}}, \sigma_{eq1}, \sigma_{eq2}, f_1 \)

If \( f_1 \geq 0 \)

No

Viscoplastic Deformation: \( \Delta \varepsilon_{ij}^{\text{pl}} \)

Plastic Deformation: \( \Delta \varepsilon_{ij}^{\text{el}} \)

Update:
\( \Delta \varepsilon_{ij}^{\text{el}}, \Delta \sigma_{ij} \)

\( \Delta \varepsilon_{ij}^{\text{el}} = \Delta \varepsilon_{ij} - \Delta \varepsilon_{ij}^{\text{pl}} - \Delta \varepsilon_{ij}^{\text{cr}} \)

\( \Delta \sigma_{ij} = C_{ijkl}^{\text{el}} \cdot \Delta \varepsilon_{ij}^{\text{el}} \)

User-defined Material Model

Calculate:
\( \Delta \varepsilon_{kk}^{\text{inel}} \)

\( \Delta \varepsilon_{kk}^{\text{inel}} = \Delta \varepsilon_{kk} - \Delta \varepsilon_{kk}^{\text{el}} \)

Calculate:
\( \rho \)

RD

\( \rho^{(t+\Delta t)} = \rho^t \cdot \Delta \varepsilon_{kk}^{\text{inel}} \)

Update Jacobi-Matrix: \( J \)

End of Increment

No, to the next increment

Yes

End
HIP Simulation with determined densities field in the capsule

RD [%]

Before HIP

After HIP

RD determined from experiment

Mean RD value

Δmax=5%

RD determined from experiment

Mean RD value

Basic HIP Cycle

Temperature [°C]

Pressure [MPa]

Time [s]

No.1

Homogenous

Inhomogenous
Introduction
➢ Purpose of the study
➢ Process description

Simulation of HIP Process with “Image Analyzed” Densities Distribution
➢ “Image Analyze” for investigation of initial density distribution
➢ FEM Simulation

Simulation of HIP Process with DEM simulated Densities Distribution
➢ Introduction of DEM and Modelling Approach
➢ Validation, Simulation and Comparison

Summary and Outlook
Process description

- Capsule design
- Particle size
- Initial relative density and distribution

 HIP process in general: (a) Capsule production; (b) Filling powder, tapping and vibration; (c) Evacuation; (d) Sealing capsule; (e) Applying high temperature and high pressure; (f) Full density HIPed component

- Material properties
- Process parameters (Time, Pressure, Temperature, etc.)

- Trial and error
- “Image Analyze” for Investigation of initial density distribution
- DEM-Simulation of powder flow and filling

- Trial and error
- FEM-Simulation of HIP Process
 Introduction of DEM

**Discrete Element Method (DEM)**

- mathematical description of single objects / particles / granules
- meshless method compared to FEM
- interactions between objects only at contact points

**Advantages:**
- Few equations which have to be solved for each object
- Forces and motions can be investigated for each single object, which are usually not measurable

**Limits in usage:**
- Computing time-consuming for real particle systems consists of billions of elements
DEM Modelling Approach

Pre-Processing

Geometries:
CAD and Mesh

Get initial values:
$\Delta t$, $r_{bin}$, $E$, $\nu$, $c_{friction}$, $c_{restitution}$,
$c_{rolling}$, $r_{particle}$, $\rho_{particle}$, ...

Newton’s law of motion
force + momentum

Force displacement law
- Relative motion
- Hertz contact model

Position of all particles
and contacts

Contact forces
- Particles and particles
- Particles and walls

DEM Solver
[High-Performance Computing]

Post-Processing

Relative Densities
Distribution

Analyzes and
graphical
output
Materials and Model Parameters

Materials:
- Stainless Steel 316L (Powder)
- SS304 (Underlayment)

Particles: radius 250 µm

Density $\rho$ 7800 kg/m³
Particle radius $r$ 250 µm
Young’s modulus $E$
Poisson’s ratio $\nu$
Coefficient of restitution $c_{\text{restitution}}$
Coefficient of static friction $c_{\text{friction}}$
Coefficient of rolling friction $c_{\text{rolling}}$

Capacity: $10^9$ Particles
- Iron powder 500 kg
- Ti-Alloys powder 300 kg

Rayleigh time increment:
$$\Delta t_R = \frac{\pi r \sqrt{\rho/G}}{(0.1631 \nu + 0.8766)}$$

Hertz time increment:
$$\Delta t_H = 2.87 \left[ \frac{(\rho(4/3)\pi r^3)^2}{rE^2v_{\text{max}}} \right]^{0.2}$$

$$\Delta t = 0.20 \min(\Delta t_R, \Delta t_H)$$

Time increment 0.000001s
Validation - Flow test

Angle of repose

Deviation: 2.9%

Relative Density [-]

30.8°

31.7°
Validation - Flowmeter

**Experiment**

**Simulation Model**

*Flowmeter*

\[\varnothing 28 \pm 0.5^\circ\]
Validation - Flowmeter

SS316L Powder
Time: Exp. 18.5 s / 50g, Sim. 20.1s / 50g
Deviation: 1.6 s , 10.2 %
Validation - Filling and HIP Simulation

Filling process using DEM Simulation

Z = 0

Relative Density [-]
Validation - Filling and HIP Simulation

Filling process using DEM Simulation

Z = 0

[Diagram showing a 3D representation of a filling process with a color-coded relative density plot on the right side.]
HIP Simulation with determined densities field in the capsule

Relative Density [-]

DEM -> FEM

three dimensional densities field

RD [- ]
0.63
0.61
0.59
0.57
0.55
0.53
0.51
0.49
0.47
0.45
0.43
HIP Simulation with determined densities field in the capsule

Cylinder Capsule
Thickness: 1.5 mm
Element size ~2 mm
Capsule material: SS304
Powder material: SS316L
Comparison of initial and final shapes

DEM Simulated

„Image Analyse“

Contours of final shape

Initial RD input from
DEM Simulation
Image Analyse

Initial Relative Density (RD)

Δmax = 3.8%

Difference: ~2%
Introduction
- Purpose of the study
- Process description

Simulation of HIP Process with “Image Analyzed” Densities Distribution
- “Image Analyze” for investigation of initial density distribution
- FEM Simulation

Simulation of HIP Process with DEM simulated Densities Distribution
- Introduction of DEM and Modelling Approach
- Validation, Simulation and Comparison

Summary and Outlook
Conclusion and Outlook

• Summary

➢ Simulation approach with coupled DEM and FEM Modelling has been used to calculate the capsule filling densities and predict the densification behavior of HIP Process.
➢ The simulation results correspond well with the experimental measurement.

• Outlook

➢ Influences of particle size distribution
➢ Influences of pre-desification process, vibration and tapping
➢ Influences of more complex shape
Sim. and Exp. of HIP Process chain

Inhomogeneous initial density distributions

“Image Analyze”

DEM Simulation

Temperature gradient on the capsule surfaces

Capsule thickness

Properties of powder and capsule materials

Kuhn-Donwey and Abouaf-Chenot Model

Temperature and pressure profile

Comparison with experiments

Capsule shape optimization

Optimized capsule

Before and after HIP
Acknowledgement

This work was performed under the support from the RWTH Aachen University HPC Compute Project No. rwth0248.

Thank you very much for your attention!

Yuanbin Deng

IWM – Institute for Materials Applications in Mechanical Engineering
RWTH Aachen University
Augustinerbach 4
52062 Aachen

www.iwm.rwth-aachen.de