Consolidation and hardening of PM-HIP hot work tool steel H13 in a single step process: Experiment and Simulation

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Introduction

Hot Isostatic Pressing

HIP-Process

1. Capsule production
2. Filling powder and pre-consolidation
3. Evacuation
4. Sealing
5. Hot isostatic pressing
6. HIPed component
Motivation

Conventional HIP and Heat treatment

- Temperature [°C]
  - Time [h]
  - Heat-treating furnace
  - HIP-Chamber

HIP with integrated rapid cooling

- Temperature [°C]
  - Time [h]
  - Combined HIP-unit

Advantages

Reducing:
- Time
- Energy
- Process infrastructure and
- The risk of cracking during hardening
Content

1 Introduction and motivation
2 Experiments and material characterization
3 Process Modelling and Simulation in ABAQUS
4 Results and discussion
5 Outlook
Experimental setup

HIP-unit

Sample

Material

Capsule:
Stainless steel 304 (1.4301)

Compact:
Gas atomized powder (60-200 µm)
Hot work tool steel H13 (1.2344)
C0.38 Cr5.2 Mo1.2 V0.91 Si1.08 Mn 0.38 [%]
**Temperature-Pressure profile**

**Cycle 1**
Max. temperature = 1075 °C  
holding time = 3 hours  
Pressure = 170 MPa  
Cooling rate = 30 °C/s

**Cycle 2**
Max. temperature = 1175 °C  
holding time = 3 hours  
Pressure = 170 MPa  
Cooling rate = 0.3 °C/s
Material model for HIP-cycle

Mechanical Analysis

- Elastic, Plastic $\varepsilon^{el}, \varepsilon^{pl}$
- Creep $\varepsilon^{cr}$
- Thermal Expansion $\varepsilon^{th}$

Material properties (temperature and density dependent)

$\lambda(T, \rho), c_p(T, \rho), E(T, \rho), \nu(T, \rho)$

Initial density

Densification analysis

Mass Conservation

Pressure

Temperature

input

Strain, Stress (deformation)

updated density

inelastic strain (volume change)

output

Experiments and material

Process modelling and simulation

Results and discussion
Material model for Quenching

Thermal analysis:
- Temperature profile \( T, \dot{T} \)
- Thermal analysis:
  - \( \lambda(T, \xi_i), c_p(T, \xi_i), \rho(T, \xi_i) \)
- Latent heat
- Metallurgical analysis:
  - Phase fractions \( \sum_i \xi_i = 1 \)
- Mechanical analysis:
  - Elastic, Plastic \( \varepsilon^{el}, \varepsilon^{pl} \)
  - Thermal Expansion \( \varepsilon^{th} \)
  - Transformation strain \( \varepsilon^{tr} \)
  - Transformation plasticity \( \varepsilon^{tp} \)

Material properties:
- (temperature and phase dependent)
  - \( E(T, \xi_i), v(T, \xi_i), \sigma_y(T, \varepsilon^{pl}, \xi_i) \)

Input:
- thermal conditions

Output:
- microstructure
- residual stress

Experiments and material | Process modelling and simulation | Results and discussion
Simulation of the HIP-cycle
Visualization of deformation and density

Experiments and material
Process modelling and simulation
Results and discussion

Video
Cross section of the sample qualitative comparison

Experiment

Simulation-after quenching

20 mm
Cross section of the sample quantitative comparison

Simulation

<table>
<thead>
<tr>
<th></th>
<th>HIP + slow cooling</th>
<th>[mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dimension</strong></td>
<td><strong>Initial</strong></td>
<td><strong>Experiment</strong></td>
</tr>
<tr>
<td>H1</td>
<td>44.5</td>
<td>40.55</td>
</tr>
<tr>
<td>H2</td>
<td>44.5</td>
<td>36.31</td>
</tr>
<tr>
<td>H3</td>
<td>44.5</td>
<td>29.09</td>
</tr>
<tr>
<td>D1</td>
<td>44.5</td>
<td>38.84</td>
</tr>
<tr>
<td>D2</td>
<td>44.5</td>
<td>41.87</td>
</tr>
<tr>
<td>D3</td>
<td>44.5</td>
<td>42.59</td>
</tr>
</tbody>
</table>

**Cycle 2**
Max. temperature = 1175 °C
holding time = 3 hours
Pressure = 170 MPa
Cooling rate = 0.3 °C/s
Microstructure of the HIPed sample needle shape structure

Process
- temperature = 1175 °C
- holding time = 3 hours
- Pressure = 170 MPa
- Cooling rate = 0.3 °C/s

Sample preparation
- Polished and etched with nital (a solution of alcohol and nitric acid)
Microstructure of the HIPed sample grain growth towards capsule

**Process**
- temperature = 1175 °C
- holding time = 3 hours
- Pressure = 170 MPa
- Cooling rate = 0.3 °C/s

**Sample preparation**
Polished and etched with nital (a solution of alcohol and nitric acid)

Sample preparation
Polished and etched with nital (a solution of alcohol and nitric acid)

Capsule

Tool steel

Process temperature = 1175 °C
holding time = 3 hours
Pressure = 170 MPa
Cooling rate = 0.3 °C/s

Sample preparation
Polished and etched with nital (a solution of alcohol and nitric acid)

Capsule

Tool steel

200 µm
Microstructure of the HIPed sample
Dark field graph

Process
- temperature = 1175 °C
- holding time = 3 hours
- Pressure = 170 MPa
- Cooling parameter = 0.3 °C/s

Sample preparation
- Polished and etched with nital
  (a solution of alcohol and nitric acid)

Capsule Tool steel

200 µm
Hardness of the HIPed samples

![Graph showing hardness [HV10] vs. distance from the left side [mm] for Sample 1 and Sample 2.]

**Cycle 1**
- Max. temperature = 1075 °C
- Holding time = 3 hours
- Pressure = 170 MPa
- Cooling rate = 30 °C/s

**Cycle 2**
- Max. temperature = 1175 °C
- Holding time = 3 hours
- Pressure = 170 MPa
- Cooling rate = 0.3 °C/s
Simulated phase fractions

**Sample 1**

- **Austenite**
- **Martensite**

**Sample 2**

- **Austenite**
- **Bainite**
- **Martensite**

**Cycle 1**

Max. temperature = 1075 °C  
holding time = 3 hours  
Pressure = 170 MPa  
Cooling rate = 30 °C/s

**Cycle 2**

Max. temperature = 1175 °C  
holding time = 3 hours  
Pressure = 170 MPa  
Cooling rate = 0.3 °C/s
Simulation of the Quenching Residual Stresses – Cycle 1

Von Mises Stress [MPa]

Max principle Stress (abs) [MPa]
Simulation of the Quenching Residual Stresses – Cycle 2

Von Mises Stress [MPa]

Max principle Stress (abs) [MPa]
Outlook

- Effect of pressure on
  - phase transformations
  - Heat convection during quenching

- Austenite grain growth

- Effect of austenite grain size on:
  - Phase transformations
  - Mechanical properties

- Precipitations

- Diffusion between powder and capsule

- Effect of oxidation and powder quality

- Residual stress measurements
Thank you for your attention

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Microstructure of the HIPed sample needle shape structure

Process
temperature = 1075 °C
holding time = 3 hours
Pressure = 170 MPa
Cooling parameter = 0.1 →
(t_{800} – t_{500} = 100 s)

Sample preparation
Polished and etched with nital
(a solution of alcohol and nitric acid)