Primary Shaping – Powder Metallurgy

Manufacturing Technology II
Lecture 2

Laboratory for Machine Tools and Production Engineering
Chair of Manufacturing Technology

Prof. Dr.-Ing. Dr.-Ing. E.h. F. Klocke

Structure of the lecture „Primary Shaping- Powder Metallurgy“

Introduction: Variety of Applications of Powder Metallurgy
Powder Production and Powder Properties
Powder Compaction
Constructions of Compaction Tools
Sintering – Basics and Examples of Sintering Furnances
Sizing
Compendium of PM Manufacturing Technologies
Comparison of the PM Manufacturing Technologies
Summary
Structure of the lecture „Primary Shaping- Powder Metallurgy“

- Introduction: Variety of Applications of Powder Metallurgy
  - Process Steps
  - Applications
- Powder Production and Powder Properties
- Powder Compaction
- Constructions of Compaction Tools
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Process Steps of Powder Pressing

- Powder
- Mixing
- Pressing
- Sintering
- Sizing

- Lubricant
- Graphite
- Bronce Powder
- Alloyed Powder
- Iron Powder
Application for Gear Boxes

source: Sinterstahl GmbH, Füssen

Applications in Automotive Engines

source: Sinterstahl GmbH, Füssen
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  - Powder Production Technologies
  - Powder Properties
  - Alloying Methods
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Powder Production: Chemical Reduction, Sponge Iron Powder

1 Reduction Mix of Coke Breeze and Limestone
2 Iron Ore
3 Drying
4 Crushing
5 Screening
6 Magnetic Separation
7 Charging in Ceramic Tubes
8 Reduction in Tunnel Kilns (1200°C)
9 Discharging
10 Coarse Crushing
11 Storage in Silos
12 Crushing
13 Magnetic Separation
14 Grinding and Screening
15 Annealing in Belt Furnace, approx. 800-900°C
16 Equalising
17 Automatic Packing
18 Iron Ore
19 Reduction Mix

source: Höganäs
**Powder Production: Water-Atomizing-Process**

- **Principle**
  Atomizing the Melting by Means of Water Jet

- **Metal**
  Scrap, Iron Ore, Roll Scale

- **Factors of Influence**

<table>
<thead>
<tr>
<th>Water Pressure</th>
<th>Melting Temperature</th>
<th>Flowrate of the Melting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grain Size</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Product**
  Pure Iron or Alloy

  Source: Höganäs, EHW Thale

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**Characterization of Iron and Steel Powder**

1. **Metallurgical Properties**
   - Chemical Composition ⇒ Chemical Analysis
   - Texture of Powder Particles ⇒ Polished Cross Sections
   - Micro Hardness ⇒ Hardness Measurement

2. **Geometrical Properties**
   - Particle Size Distribution ⇒ Sieve Analysis
   - External Practical Shape ⇒ Scanning Electron Microscopy
   - Internal Particle Structure (Porosity) ⇒ Metallographic Cut through the Powder Particle

3. **Mechanical Properties**
   - Flow Rate ⇒ Hall-Flowmeter (Standardized Cone)
   - Bulk Density ⇒ Filling a Bowl with a Standardized Cone
   - Compressibility ⇒ Pressing Standardized Stopper, results presented as a curve
   - Green Strength ⇒ Fatigue Strength of a Pressed Square Test Bar
   - Spring-Back ⇒ Elastic Extension of a Pressed Stopper, d=25 mm
Particle Form and – Structure of Unalloyed Iron Powder

Sponge Iron Powder
NC 100.24

Atomized Powder
ASC 100.29

source: Höganäs

Alloying Methods of Iron Powders

Completely Alloyed Powder

Mixed Alloyed Powder

Partially Alloyed Powder
Alloying Methods of Iron Powders

<table>
<thead>
<tr>
<th>Completely Alloyed Powder</th>
<th>water-atomized powders, at which the molten material consists of the required alloying elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixed Alloyed Powder</td>
<td>powder-mixes consisting of at least 2 pure alloying components</td>
</tr>
<tr>
<td></td>
<td>long sintering times and high sintering temperatures necessary for homogenizing</td>
</tr>
<tr>
<td>Partially Alloyed Powder</td>
<td>diffusion alloyed: annealing of mixed powders</td>
</tr>
<tr>
<td></td>
<td>adhesion alloyed: usage of alloying elements which can’t be bound on iron by a diffusion process</td>
</tr>
</tbody>
</table>

Structure of the lecture „Primary Shaping- Powder Metallurgy“

- Introduction: Variety of Applications of Powder Metallurgy
  - Powder Production and Powder Properties
    - Powder Compaction
      - Compendium
      - Filling
      - Pressing
      - Ejection
  - Constructions of Compaction Tools
  - Sintering – Basics and Examples of Sintering Furnaces
  - Sizing
  - Compendium of PM Manufacturing Technologies
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The Compaction Cycle

Filling

Upper Punch

Fill Shoe

Green Compact

Compacting

Compact

Ejecting

Green Compact

Die

Lower Punch

Powder

Green Compact
Filling: Contour Filling

Without contour filling  
With Contour Filling

source: Osterwalder

Filling: Formation of Bridges when Filling Narrow Cross-Sections

Formation of bridges when filling narrow cross-sections

When high homogeneity requirements of the components:

Pressed height of the component \( h < 15 \text{ mm} \): \( d > 2.5 \text{ mm} \)
Pressed height of the component \( h > 15 \text{ mm} \): \( d > h/6 \)
**Filling: Empirical Pressure-Density-Curve Defined at a Column of Powder**

![Graph showing the relationship between compaction pressure and compressed density.](image)

**Pressing: Decreasing of the Axial Stress \( \sigma_a \) During Compaction**

Frictional forces at the wall of the compacting die restrain the compaction of the powder. With increasing distance from the face of the compacting punch, the axial stress \( \sigma_a \), which is available for the local densification of the powder, decreases.

\[
\sigma_a(x) = \sigma_a(0) e^{-2\mu/r}
\]

source: Höganäs
Pressing: Compacting Methods Used for the Production of Compacts

One-Sided Compacting

Two-Sided Compacting

Compacting with Floating Die

Pressing: Influence of the Density on the Material Properties

Calculation of Material Properties

\[
\frac{1 + \nu_p}{1 + \nu_0} = \left( \frac{\rho}{\rho_0} \right)^m \quad \frac{P}{P_0} = \left( \frac{\rho}{\rho_0} \right)^m
\]

- \( \rho \): Density
- \( \rho_0 \): Full Density
- \( P \): Material Properties
- \( P_0 \): Material Properties of the Raw Material
- \( m \): Powder Coefficient

Material Data of the P/M-Steel: Distaloy HP-1: Fe-1.5Mo-4.0Ni-2.0Cu

<table>
<thead>
<tr>
<th>Material Property</th>
<th>Powder Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Conductivity</td>
<td>1.5 ... 3.5</td>
</tr>
<tr>
<td>Young’s Modulus</td>
<td>2.5 ... 4.5</td>
</tr>
<tr>
<td>Dynamic Strength</td>
<td>3.5 ... 5.5</td>
</tr>
<tr>
<td>Notched Impact Strength</td>
<td>&gt;12</td>
</tr>
</tbody>
</table>

- Poisson’s Ratio
- Young’s Modulus
- Dynamic Strength
Ejection: Ejection Procedure

**Steps:***

1. **Filling-Position**: Upper Punch and Powder are placed inside the die.
2. **Compaction-Position**: Bottom Ram and Die Bolster are used to compact the Green Compact.
3. **Pressure-Relief**: The compact is released from the die bolster.
4. **Ejection-Position**: The compact is ejected using the ejector pin.

Source: Fachverband für Pulvermetallurgie

Withdrawal: Withdrawal Procedure

**Steps:***

1. **Filling**: Upper Punch introduces Powder into the die.
2. **Compacting**: The compact is formed using the die and Bottom Ram.
3. **Lifting**: The compact is lifted using the lift mechanism.

Source: Fachverband für Pulvermetallurgie
Ejection: Schematic Diagramm of the Ejection Force

Ejection Force

Punch Travel

source: Höganäs

Ejection: Cracking Risk when Removing the Compact

Crack Formation at the Compact

Different elastic expansions of two lower punches

Ejection procedure at a sharp edge of the die

Avoiding crack formation by tapering the die exit and rounding-off the upper rim of the die!

source: Höganäs

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Fraunhofer Institut für Produktionstechnologie
Ejection: Spring-Back as a Function of Compact Density

\[ S(\%) = 100 \left( \frac{\lambda_d - \lambda_s}{\lambda_s} \right) \]

- **S**: Spring-Back in %
- **\( \lambda_d \)**: Transversal Dimension of the (ejected) Compact
- **\( \lambda_s \)**: Corresponding Dimension of the Compacting Die (After Ejection of the Compact)

**Parameters Influencing the Spring-Back**
- Compacting Pressure, Compacting Density, Powder Properties, Lubricants and Alloying Additions, Shape & Elastic Properties of the Compacting Die

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Principle of a Compaction Tool with a Split Die

Component

1. Upper Punch
2. Fill Shoe
3. Upper Part of the Die, moveable
4. Lower Part of the Die, fixed
5. Bottom Rod
6. Core Pin

Filling

Compacting

Opening

Lifting

source: Gräbener

Compaction Tool: Powder Compaction of Helical Gear

Powder Compaction

1. Filling
2. Underfill by Die Lift
3. Closure of Die
4. Powder Transfer with Inner Punches
5. Compaction
6. Die Withdrawal with Upper Punch and Core Rod Withdrawal
7. Full Demoulding by Inner Punch and Core Rod Withdrawal
Compaction Tool: Cross Hole and Complex Part with Different Filling Heights

Compaction of a Part With a Cross Hole

Compaction of a Part with Different Filling Heights

source: Osterwalder

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Sintering: Different Atmospheres in a Sintering Conveyor Furnace

Room Temperature

Temperature

zone 1: 150°C
zone 2: 700°C
zone 3: 850°C
zone 4: 1120°C

Smoke and Gas Outlet

Gas Inlet

Zone 1: Burning-Off Lubricants
Zone 2: Sintering
Zone 3: Re-Carbonizing
Zone 4: Cooling

Source: Höganäs

Sintering: Diffusion Types at Sintering

Parameters Influencing the Diffusion:
- Temperature
- Time
- Composition of Alloy

Legend:
- v: Volume Diffusion
- s: Surface Diffusion
- b: Grain Boundary Diffusion
- e: Evaporation/Condensation
- f: Forces from Surface Tension (viscous flow)

source: Kuczynski
Sintering: Influence of Sintering Time on the Material Properties

![Graph showing the influence of sintering time on material properties: density, tensile strength, and elongation at different sintering temperatures (850°C and 1150°C).]

Different concepts of sintering furnaces

- conveyor furnace
- pusher type furnace
- roller hearth furnace
- walking-beam furnace

*source: Höganäs*
Sizing

Sizing involves reduction or increase in the dimensions of the component, and this action is performed by forcing the component into a die or over a core.

- Hardness of the part to be sized should not exceed HV 180 after sintering.
- Wherever possible, the various surfaces of the part should be sized progressively and not simultaneously.
- The external forms should be sized before the holes in order to prevent cracking.

Quelle: Höganäs
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Process Sequences in PM-Technology 1

- **Pressureless Sintering**
  - Powder Production
  - Pouring
  - Sintering
  - Sizing
  - Oil Impregnation

- **Infiltration**
  - Powder Production
  - Compaction
  - Sintering
  - Infiltration
  - Machining

- **High-Porous Components**
  - e.g.: Filters, Flam Traps, Throttles
  - Quelle: GKN

- **Pore Free Components**
### Process Sequences in PM-Technology 2

<table>
<thead>
<tr>
<th>Conventional Sintering</th>
<th>Warmcompaction</th>
<th>Double Pressing</th>
<th>Powder Forging</th>
</tr>
</thead>
<tbody>
<tr>
<td>Powder Production</td>
<td>Powder Production</td>
<td>Powder Production</td>
<td>Powder Production</td>
</tr>
<tr>
<td>Compaction</td>
<td>Compaction (150°C)</td>
<td>Compaction</td>
<td>Compaction</td>
</tr>
<tr>
<td>Sintering</td>
<td>Sintering</td>
<td>Sintering</td>
<td>Sintering</td>
</tr>
<tr>
<td>Sizing</td>
<td>Sizing</td>
<td>Sizing</td>
<td>Sintering</td>
</tr>
<tr>
<td>Heat Treatment</td>
<td>Heat Treatment</td>
<td>Machining</td>
<td>Re-Sintering</td>
</tr>
<tr>
<td>Machining</td>
<td>Machining</td>
<td>Machining</td>
<td></td>
</tr>
</tbody>
</table>

### PM Technology: Powder Forging

<table>
<thead>
<tr>
<th>Powder Forging</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compaction</td>
</tr>
<tr>
<td>Weight Control</td>
</tr>
<tr>
<td>Sintering</td>
</tr>
<tr>
<td>Inductive Heating</td>
</tr>
<tr>
<td>Automatic Handling</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Forging</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_{\text{Forge}} \rightarrow T_{\text{Recrystallisation}} )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Heat Treatment</th>
</tr>
</thead>
</table>
PM Technology: Metal Injection Moulding MIM

Metal Injection Moulding

Powder:
Grain Size: < 12 µm,
Round Grain Form
(Gas Atomised)

Mixing
Pelleting
Extrude/Inject
Debinding:
Chemic / thermal
Sintering

Highlights:
High Added Value
Complex Geometry
Component Mass: m < 500 g
Thickness: s < 30 mm,
Debinding Time: t ~ s^2
High Densities
High Shrinkage

PM Technology: MIM Applications

<table>
<thead>
<tr>
<th>Gearing parts</th>
<th>Watchcase</th>
<th>Medicine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Application: Synchronising</td>
<td>Application: Watchcase</td>
<td>Material: Nickel Free, Stainless Steel</td>
</tr>
<tr>
<td>Density: &gt; 7.4 g/cm³</td>
<td>G-Shock</td>
<td>Density: 7.6 g/cm³</td>
</tr>
<tr>
<td>Heat Treat.: Case Hardening</td>
<td>Material: Titan Alloy</td>
<td>Yield strength: 552 N/mm²</td>
</tr>
<tr>
<td>Tensile Strength: &gt; 450 MPa</td>
<td>Density: 4.38 g/cm³</td>
<td>Tensile Strength: 657 N/mm²</td>
</tr>
<tr>
<td>Mass: ca. 28 g (1)</td>
<td>Waterproof up to 200m</td>
<td></td>
</tr>
<tr>
<td>ca. 6 g (2, 3)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Quelle: (1) GKN; (2) (3)

© WZL / IPT
PM Technology: Isostatic Pressing

Isostatic Compaction
- Up to 100% Density
- No Density Gradients
- Great Material Spectrum
- Low Cycle Time

Mould Filling
Fluid Filling
Applying Pressure
Fluid Discharge
Handling
Sintering

1
2
3

Up to 100% Density
No Density Gradients
Great Material Spectrum
Low Cycle Time
PM Technology: Surface Densification by Transverse Rolling

**Process Conditions**
- **Workpiece:**
  - Initial Density: \( \rho_{\text{ges,0}} \)
  - Gradient of Overmeasure: \( a(s) \)
- **Tool:**
  - Tool Geometry
- **Process:**
  - Transverse Rolling Force: \( F_{\text{Walz}} \)
  - Infeed: \( f \)
  - Rolling: \( M_{\text{Walz}} \) or Braking Torque: \( M_{\text{Brems}} \)
  - Number of Cycles: \( n_0 \)

**Process Results**
- **Workpiece:**
  - Densification Gradient
  - Densification Depth: \( t_{0.98\%} \)
  - Gear Tooth Quality
- **Tool:**
  - Load: \( F \)
  - Stress: \( \sigma \)
  - Deformation: \( \varepsilon \)

---

PM Technology: Typical Deviations of Surface Densified P/M Gears

- **Profile Deviation**
  - Positive Pressure Angle
  - Negative Crowning
  - Asymmetric Profile on the right and left Flank

- **Densification Defects**
  - Incomplete Densification in Highly Loaded Areas
  - Asymmetric Densification on left and right Flank

Source: Höganäs AB
PM Technology: FE Model of Surface Densification by Rolling

- **Objects**
  - Rigid Tool
  - Rigid Shaft
  - Porous P/M Gear
    - Number of Elements: 3374
    - Number of Nods: 3580
    - Weighted Mesh

- **Interobject Conditions**
  - Shaft - P/M-Gear: Sticking
  - Tool - P/M-Gear: Contact

- **Simulation Parameters**
  - Step: \( \Delta t = 0.0005s \)
  - Direct Method Iteration
  - Calculation Time: 6h/cycle

PM Technology: Comparison of the Density Gradient determined through Simulation and Experiments

- **Comparison of the Density Gradient determined through Simulation and Experiments**
  - High Densification in the Addendum
  - Nonuniform Densification on the left and right Flank
  - Incomplete Densification on the right Flank
  - Nonuniform Densification of the right and left Tooth Root
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Comparison: Production Costs

- Costs:
  - Low
  - Middle
  - High

- Density [g/cm³] (Strength)
  - 7.2
  - 7.4
  - 7.6
  - 7.8

- Technologies:
  - Conventional Compaction
  - Warm Compaction
  - Double-Process Sintering
  - Powder Forging
  - Local Densification
  - MIM
Comparison: Geometrie Complexity

- Conventional Compaction
- Warm Compaction
- Double Process Sintering
- MIM
- Powder Forging
- Local Densification

Density [g/cm³] (→ Strength)

Comparison: Precision

- Conventional Compaction
- Warm Compaction
- Double-Process Sintering
- Selective Densification
- Powder Forging
- MIM

Density [g/cm³] (→ Strength)
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Conclusion: Principle, Advantages and Limits of P/M Technology

Advantages of P/M Technology
- Low Costs at Series Production
- High Quality at Series Production
- Net-Shape Technology
- Extensive Alloying Possibilities
- Weight Reduction Because of Porosity
- 100% Raw Material Utilisation
- Low Energy Consumption
- Freedom in Profile Design

Limits of P/M Technology
- Density Dependent Properties
- Undercuts, Cross Holes and Thread not Producible by Pressing
- Maximum Weight of Component 1 kg

Proceeding of Single Process Sintering:
- Powder Mixing
- Pressing
- Sintering
- Sizing

Sintered Components:
- Test Gear
- Camshaft Gear

Source: Höganäs AB
Source: Miba AG
The classification of sintered steels primarily acts upon the copper-content and the mass of the remaining alloying elements. With SINT: sintered material.

**character:**

1st digit: material composition

2nd digit: serial number

| 0 | sintered steel with percentage weight of 0% - 1% Cu, with or without C |
| 1 | sintered steel with percentage weight of 1% - 5% Cu, with or without C |
| 2 | sintered steel with percentage weight of more than 5% Cu, with or without C |
| 3 | sintered steel with or without Cu, with or without C, but with a percentage weight of up to 6% of other alloying elements |
| 4 | sintered steel with or without Cu, with or without C, but with a percentage weight of more than 6% of other alloying elements |
| 5 | sintered alloys with a percentage weight of more than 60% Cu |
| 6 | sintered metals which are not included in no. 5 |
| 7 | sintered light metals, e.g. sintered aluminium |

**Classes of sintered steel according to porosity**

<table>
<thead>
<tr>
<th>material class</th>
<th>porosity $P$ [%]</th>
<th>sintered density ratio $R_s$ [%]</th>
<th>preferred applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>SINT - AF</td>
<td>&gt; 27</td>
<td>&gt; 73</td>
<td>filter, flame traps, throttles</td>
</tr>
<tr>
<td>SINT - A</td>
<td>25 ± 2,5</td>
<td>75 ± 2,5</td>
<td>plain bearings</td>
</tr>
<tr>
<td>SINT - B</td>
<td>20 ± 2,5</td>
<td>80 ± 2,5</td>
<td>plain bearings, seals, guide rings, structural parts for low loads</td>
</tr>
<tr>
<td>SINT - C</td>
<td>15 ± 2,5</td>
<td>85 ± 2,5</td>
<td>plain bearings, sliding pats, medium-strength parts, e.g. shock absorber parts, oil pump gears</td>
</tr>
<tr>
<td>SINT - D</td>
<td>10 ± 2,5</td>
<td>90 ± 2,5</td>
<td>high-strength parts for high static and moderate dynamic loads</td>
</tr>
<tr>
<td>SINT - E</td>
<td>6±1,5</td>
<td>94 ± 1,5</td>
<td>high-strength parts for high static and high dynamic loads</td>
</tr>
<tr>
<td>SINT - F</td>
<td>&lt;4,5</td>
<td>&gt; 95,5</td>
<td>warm-compacted parts for highest loads</td>
</tr>
<tr>
<td>SINT - G</td>
<td>&lt; 8</td>
<td>&gt; 92</td>
<td>with plastic or metal impregnated parts, high corrosion resistance, impermeable for oil and water</td>
</tr>
<tr>
<td>SINT - S</td>
<td>&lt; 10</td>
<td>&gt; 90</td>
<td>warm-compacted plain bearings and sliding elements with internal solid lubricant</td>
</tr>
</tbody>
</table>
# Tolerances of different shaping processes

<table>
<thead>
<tr>
<th>Process</th>
<th>ISO-Quality IT</th>
</tr>
</thead>
<tbody>
<tr>
<td>conventional PM-technology</td>
<td>5  6  7  8  9  10  11  12  13  14  15  16</td>
</tr>
<tr>
<td>powder forging</td>
<td></td>
</tr>
<tr>
<td>conventional PM-technology with sizing</td>
<td></td>
</tr>
<tr>
<td>investment casting</td>
<td></td>
</tr>
<tr>
<td>diecasting</td>
<td></td>
</tr>
<tr>
<td>forming under compressive conditions, hot extrusion</td>
<td></td>
</tr>
<tr>
<td>warm working extrusion</td>
<td></td>
</tr>
<tr>
<td>cold extrusion</td>
<td></td>
</tr>
<tr>
<td>turning</td>
<td></td>
</tr>
<tr>
<td>cylindrical grinding</td>
<td></td>
</tr>
</tbody>
</table>

All tolerances are rough values and depend on the size of the components and on the material!

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# Catalogue of questions to summarize the lecture „Powder metallurgy“

1. Explain the two significant methods for powder production, the methods for the characterization of metal powders and the three different alloying techniques!
2. Sketch the phases of compaction (use a cylindrical compact)!
3. Explain the terms density distribution, ejection force and spring-back!
4. Explain an industrial sintering process on the basis of a sintering conveyor furnace!
5. Explain the reasons for a sizing operation!
6. Explain then a sizing operation, as example use e.g. the ball sizing of bushes!
7. Specify and explain the schematic flow of conventional PM-processes!
8. Which possibilities are provided by PM-technology for producing highly loaded parts?
9. Specify and explain the influencing parameters on the production costs of PM-parts!