Andreas Sterzing

Innovation in Forming Technology – Solution Potentials of Future Challenges
Focus: Realization of Powertrain Components

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1 Introduction
Production-Relevant Megatrends (selected)

large **social, economic, political** and **technological changes**
(John Naisbitt)

**Rising world population**
- markets in growth regions
- growing demands

**Demographic development**
- aging of population
  (changing working conditions)
- down aging

**Sustainability**
- efficiency in product realization / operation
- shortage of resources
- reduction of emissions

**Individualization**
- individual, user-specific products
- complex products / production processes

**Urbanization**
- mobility
- living and production in mega cities

**Globalization**
- products / technologies for global markets
- global standards
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2 Relevance for Production / Forming Technologies

Efficiency is becoming increasingly important.

- **Efficiency Increase in Product Operation**
  - reduction of energy use
  - reduction of emissions

- **Lightweighting**

- **Influencing of Part Characteristics**
  (incl. material design)

- **Efficiency Increase in Product Manufacturing**
  - reduction of resource use
    (material, energy, time, human, ...)

- **Alternative Process Routes**
  - shortening / optimization
    (e. g. use of net-shape technologies)

- **Process Safety / Stability**
  - virtual process development
  - process monitoring / influencing / control

- **Flexibility** (process, tool, machine)

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not only in automotive industry

- rail vehicle industry
- aircraft industry
- shipbuilding
- construction vehicles
- agricultural machines
- power generation
- ...
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3 Efficiency Increase in Product Operation
Innovative Components for Ship Powertrains

**Today’s Situation**

- world fleet (approx. 90,000 ocean-going ships)
- 370 mio. tons fuel (mostly heavy oil)
- emission
  - sulphur oxides \( \text{SO}_x \) 13%
    (20 mio. tons)
  - carbon dioxide \( \text{CO}_2 \) 3%
  - nitrogen oxides \( \text{NO}_x \) 15%
  - sooty particles
  - fine dust

**Challenges**

- significant reduction of emissions
- establishment of **ECAs**
  (emission controlled areas)
- implementation of emission **standards**
  TIER I...III \( \rightarrow \) soot, \( \text{NO}_x \)
  TIER IV (from 2020) \( \rightarrow \) additionally \( \text{SO}_x \)
3 Efficiency Increase in Product Operation
Innovative Components for Ship Powertrains

Potentials of Inland Water Transportation

➔ most efficient transport method

comparison of transport costs

➔ reduction of emissions

waterways (Germany)
3  Efficiency Increase in Product Operation
Innovative Components for Ship Powertrains

Approach / Promising Measures

- **optimization of combustion behaviour**
  - increase of combustion *temperature* ($\vartheta = 500^\circ\text{C} \rightarrow \vartheta = 650^\circ\text{C}$)
  - average cylinder *pressure* ($p = 25\text{ bar} \rightarrow p = 40\text{ bar}$)

- increase of *thermal* and *mechanical loading* of engine *components*
- use of *new material compounds* for *valves* and *pistons* (e. g. steel + Nimonic / Inconel)
  - strength increase
  - high-temperature stability

- **lightweighting**
  - alternative *part design* (e. g. hollow shafts)
  - *feasibility*
  - efficient *component realization*
  - technology readiness level / *series capability*

**Enabler** (efficient component realization)

- innovative *manufacturing / forming processes*
- alternative *process routes* (e. g. forming-based)
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Innovative Components for Ship Powertrains

Use of Innovative Material Compounds for Piston Head
(in consideration of higher temperatures and pressures in the combustion chamber)

- strength increase
- high-temperature stability

Systematic investigations for realization and forming of compounds

- steel (e.g., 42CrMo4)
- high-temperature alloy (e.g., Inconel 718)

Influence of
- temperature
- surface conditions
- ...

Realized piston head (D = 160 mm)
3  Efficiency Increase in Product Operation
Innovative Components for Ship Powertrains

Use of Innovative Material Compounds for Piston Heads
(in consideration of higher temperatures and pressures in the combustion chamber)

Summary / Conclusions

- Development, application and optimization of efficient process route for hybrid piston heads using innovative material compound
  - compound realization
  - forming of compound
  - part finishing

- Proof of feasibility

- Guarantee of required part characteristics
e. g. resistance against high thermal and dynamic loading

- Transferability of method for other components
e. g. valves
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Innovative Components for Ship Powertrains

Lightweight Piston Based on Innovative Process Combination (lower part)

- Casting + Forging
  - resource **efficiency** \(\uparrow\) (time, material, energy)
  - geometrical part **complexity** \(\uparrow\)
  - realization of appropriate **property gradients** (inhomogeneous loading)

Innovation

State-of-the-art
3 Efficiency Increase in Product Operation
Innovative Components for Ship Powertrains

**Lightweight Piston Based on Innovative Process Combination** (lower part)

- **Casting**
  - scaled demonstrator components
  - derivation of **two different variants** (cast pre-forms) from selected piston design considering
    - piston loading (lower part)
    - casting requirements
    - subsequent forging process
  - design of **casting system**
    four cavities in one mould for systematic parameter investigation
  - cast trials
    \[ \theta_{\text{casting}} = 1630 \, ^\circ\text{C} +/- 15 \, \text{K} \]
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Innovative Components for Ship Powertrains

Lightweight Piston Based on Innovative Process Combination (lower part)

- Forging
  - realization of forging tool
    (design, construction, testing)
  - forging trials
    \[ T_{\text{forging}} = 1100 \, ^\circ \text{C} \]
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Innovative Components for Ship Powertrains

**Lightweight Piston Based on Innovative Process Combination** (lower part)

**Summary / Conclusions**

- **combination** of advantages of both technologies
  - design freedom of casting
  - strength increase based on forging
- completely new possibilities for **lightweighting**
- significant **resource saving** along the entire process route

**Next Steps**

- realization of lower part for a **real piston** (D = 160 mm)
- **optimization** of **casting** process
  (accelerated solidification for microstructure refinement)
- realization of **complete piston** consisting of
  - hybrid piston head
  - lightweight lower part
3 Efficiency Increase in Product Operation
Innovative Components for Ship Powertrains

Forming-Based Process Route for Hollow Gear Shafts

Initially Situation (focus: automotive powertrain)

MACHINING (State of the art):

- Solid bar
- Forging
- Deep hole drilling
- Cutting
- Gear hobbing, Deburring
- Heat treatment
- Grinding, Shot peening

Focus: Holistic Approach: forming processes from pre-forming...finishing

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3 Efficiency Increase in Product Operation
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Forming-Based Process Route for Hollow Gear Shafts

Initially Situation (focus: automotive powertrain)

ENPROK alternative process chains for manufacturing of hollow gearshafts
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Forming-Based Process Route for Hollow Gear Shafts

Initially Situation (focus: automotive powertrain)

Example: Output Shaft – Achieved Effects

- **part weight** ↓ (-22 %)
- **power density** ↑ (+28 %)
- **material use** ↓ (-36 %)
- new fixing concept
  → reduction of **notch effect**
  → improvement of bevel gear centering
- staged design
  → improved **assembling conditions** for bevel gear
- **elimination** of **hardening process**
  → hardness ↑ in spline section (+15 %)
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Forming-Based Process Route for Hollow Gear Shafts

Spin Extrusion – Realization of Hollow Preform

Principle

- realization of **hollow parts** based on a combination of **backward cup extrusion** and **flow forming**
- realization of **inner profiles** or shaft shoulders
- incremental forming process
- depending on material
  → cold or temperature-supported forming process

- axial punch clamping
- alignment of rolls to punch
- **synchronous rotation** of rolls and punch
- **synchronous axial feed** of rolls

→ **material flow**
  in opposite direction
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Forming-Based Process Route for Hollow Gear Shafts
Spin Extrusion – Technology Adaption

large shafts
($l_{\text{max}} \approx 2000 \text{ mm}; D_{\text{max}} \approx 600 \text{ mm})$
- ship industry
- aircraft industry
- energy generation
- commercial vehicles

Objectives
- technology development
- development / realization of special purpose (test) machine

Current Status
start-up of test machine
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4 Efficiency Increase in Product Manufacturing
Temperature-Supported Gear Rolling

Process Development

State-of-the-Art

First, successful research results of Fraunhofer IWU

Stub Tooth Gears

Conventional Gears

High Gears

Tooth height factor

$y = 1$

→ short, compact teeth with high strength
→ transmission of high forces / torques

Tooth height factor

$y \leq 2$

→ typical pressure angle 20°
→ use in gear manufacturing (automobile)

Tooth height factor

$h \geq 2$

→ large profile overlap
→ increased running smoothness
4 Efficiency Increase in Product Manufacturing
Temperature-Supported Gear Rolling

Process Sequence (conventional)
4 Efficiency Increase in Product Manufacturing
Temperature-Supported Gear Rolling

Advantages

**Process**
- shortening of process time (up to 50%)
- material saving (no chips up to 30%)
- low forming forces (incremental forming)

**Component**
- strain hardened surface layer
- contour related fibre orientation (no separated)
- higher contour stability after hardening
- high tooth root strengths / flank load capacity
- surface roughness ($R_a = 0.2 \ldots 0.5 \, \mu m / R_z = 1.4 \ldots 3 \, \mu m$)

Improvement of part characteristics (based on forming process)
4 Efficiency Increase in Product Manufacturing
Temperature-Supported Gear Rolling

Challenges

I Tool Optimization
- loadings (bending)
- life time

II Extension of Process Limits
- part spectrum
  - “new”, high-strength materials
  - compact gears
- increasing modules
  (m = 8 mm...12 mm)
- gear size

III Improvement of Part Quality
- improvement of quality parameters
  (dimensions, geometry)
- acoustic behaviour

IV Process Integration

use of temperature as process parameter
\( \theta_{\text{rolling}} \approx 1000^\circ \text{C} \)
4 Efficiency Increase in Product Manufacturing
Temperature-Supported Gear Rolling

Research Focus
- **process** development / optimization
- proof of **feasibility**
- improvement of part **quality**
- achievement of **series capability**

**Ring Gear**
18CrNiMo7-6
Da = 122,86 mm
m = 4 mm
z = 27

**Geared Shaft**
20MoCr4
Da = 108,25 mm
m = 4,5 mm
z = 22
4 Efficiency Increase in Product Manufacturing
Temperature-Supported Gear Rolling

Technology Adaption

large gears \((D_{\text{max}} \approx 1000 \text{ mm})\)
- energy generation
- ship industry
- commercial vehicles

Foci
- technology development
- development and realization of test machine
4 Efficiency Increase in Product Manufacturing
Potentials of Additive Manufacturing for Forming Processes

Introduction

- **additive** [from Latin] – to add, to join; in this case: building up, e. g. layer by layer, **additive**

- **Rapid Prototyping (RP):**
  additive generation of parts with limited functionality (prototypes, test parts)

- **Additive Manufacturing (AM):**
  additive manufacturing of end products / series parts

**Rapid Tooling:**
use of additive methods and processes for tool and die making

principle of additive manufacturing process
source Gebhardt, A.: Generative Fertigungsverfahren
4 Efficiency Increase in Product Manufacturing
Potentials of Additive Manufacturing for Forming Processes

**Advantages**

- **time to product**
  - no tools needed
  - no job preparation / technology planning
  - single step process

- **freedom of shape**
  - any complex geometries
  - undercuts
  - internal geometric shapes
  - delicate structures
  - geometries not producible by conventional manufacturing methods

- **material diversity**
  - aluminium
  - titanium
  - hot and cold work steel
  - nickel-based alloys (Inconel)

- **lightweight design / bionics**
  - hollow and lattice-like structures
  - 100 % topology optimized parts
  - bionic structures
  - structures with graded porosity
4 Efficiency Increase in Product Manufacturing
Potentials of Additive Manufacturing for Forming Processes

Advantages

> Realization of any complex part structures that are conventionally not realizable
e. g. by casting, cutting, forming, ...
(or only with high manufacturing effort)

> Realization of bionically inspired products

> Highest flexibility

bracket prototype (stainless steel)
Source: EOS, EADSs

nacelle
hinge bracket
(titanium)
Source: EOS, EADSs
4 Efficiency Increase in Product Manufacturing
Potentials of Additive Manufacturing for Forming Processes

Competition with Forging Technology

Statement during FIA Fall Meeting 2013
San Antonio, October 21-23, 2013
Workshops on the topic “Future Challenges”

Additive Manufacturing

“…one of the most important competitive manufacturing technologies for the American Forging Industry in the future…”
4 Efficiency Increase in Product Manufacturing
   Potentials of Additive Manufacturing for Forming Processes

Rapid Tooling

Example Rapid Tooling

→ Efficiency increase in prototype realization
   approach: realization of forming tools by additive manufacturing

Potentials
- realization of any complex geometries
  e. g. undercuts, delicate geometry areas
- material diversity (for forming tools)
- NC programming conditionally required

Challenges (Today)
- surface quality
- material (powder) costs
- manufacturing time and costs

Demonstrator “Crankshaft segment”

die insert (design)

die insert (realized)

Feasibility
- tool manufacturing
- forging process

Part quality

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4 Efficiency Increase in Product Manufacturing
Potentials of Additive Manufacturing for Forming Processes

Alternative Process Routes – Process Combination

- **additive manufacturing**
  - realization of **pre-form**
    - load-adapted, complex part design

- **forming** (e.g., forging)
  - realization of final **geometry**
  - guarantee and improvement of **part characteristics**
    - e.g., - density † (globally, locally)
    - strength † (globally, locally)
  - tailored, graded properties
  - further lightweight effects

- **part finishing**
  - surfaces

  - determination of **CAD data** (part scanning)

  - **topology analysis/optimization**

  - **re-design**

- **part finishing**

- **forming**

- **additive manufacturing**
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Industry 4.0 – Relevance for Forging Industry
Data-Driven Intelligent Production

- **BUSINESS MODELS**
  - transparent, flexible, comprehensible

- **ENERGY**
  - synchronized energy demand/supply

- **PEOPLE**
  - communicating, interacting, deciding

- **INTERACTION**
  - intuitive, close to real time, contextual

- **PRODUCTS**
  - know their properties and their history.

- **FACTORY OPERATION**
  - optimum use of available resources

- **LINKED DATA**

- **MACHINES**
  - know their abilities, can work autonomously.

- **PROCESS CHAINS**
  - configure themselves ad hoc,

- **DIGITAL FACTORY**
  - simulation, forecast-based verification

- **PRODUCTION SYSTEMS**
  - operate / adapt themselves.

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5 Industry 4.0 – Relevance for Forging Industry
Process Monitoring, Influencing and Control

Challenges

„New“ Materials
e. g. characterized by limited formability and/or high strength

Part Complexity ↑

Part Quality ↑
e. g. dimensional tolerances

Part Functionality ↑
e. g. demands on microstructure

Increase of Efficiency
- costs ↓
- resource use ↓
e. g. minimization of
→ scrap
→ try-out

monitoring / sensing strategy for forging processes
Industry 4.0 – Relevance for Forging Industry
Process Monitoring, Influencing and Control

Challenges

- **information** about
  - current forming *process*
  - process *result* / forged *part* (e.g. dimensions, failures, etc.)
  - tool *wear* / wear **development**

**Relevant parameters**
- description of process status
- related to part quality

**Available sensors** for

**Data acquisition**
- robustness/reliability
- costs
- maintenance
- capability for industrial application

**Data processing**
- derivation of information
- basis for process control / closed-loop control

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Industry 4.0 – Relevance for Forging Industry
Process Monitoring, Influencing and Control

Foci

**MACHINE**
- process parameters (provided)
- machine / component conditions → predictive maintenance

**SEMI-FINISHED PRODUCT**
- geometry / dimensions
- properties / microstructure conditions
- temperature (heating process)

**TOOLING**
- tool loading
- tool / component conditions
- wear situation / development → predictive maintenance

**PROCESS**
- process parameters (acting) → expected process result
- process-related information → basis for closed-loop control

**NEED FOR ACTIVITIES**
- identification of relevant parameters (related to process status / part quality)
- suitable sensors for data acquisition (robustness, reliability, costs, …)
- data processing

**FORGED PART**
- geometry / dimensions / quality features
- properties / microstructure
5 Industry 4.0 – Relevance for Forging Industry
Process Monitoring

Measurement of HotForgings

State-of-the-Art

➔ up to now
three-dimensional measurements of complex formed parts / geometries
➔ maximal $\vartheta \approx 200 \, ^\circ C$
(castings, forgings, moldings)

➔ “hot” parts and components
➔ laser measurement, particularly laser triangulation
(bars, tubes, slabs, thick plates)

➔ not existent
➔ three-dimensional measurement of complex, red-hot forgings at forging-relevant temperatures
(e. g. steel $\vartheta = 950...1250 \, ^\circ C$

Approach

➔ use of blue laser light
➔ red laser light on red-hot surfaces not detectable
Industry 4.0 – Relevance for Forging Industry

Measurement of Hot Forgings

Development of Methodology using Blue Laser

- detection of form and dimensional deviations

- conception and implementation of a measuring station for \( \theta_{\text{part max}} > 1000 \, ^\circ\text{C} \)

- sensor coupled with movement mechanism
  \( \rightarrow \) reduction of the thermal load caused by heat radiation

nevertheless:
additional heat protection measures for scanner and camera

- sample part made of Stellite
  \( \rightarrow \) no scale formation up to \( \theta > 1200 \, ^\circ\text{C} \)

false-colour image taken with thermal camera (CMOS)
5 Industry 4.0 – Relevance for Forging Industry
Process Monitoring

Measurement of Hot Forgings

Development of Methodology using Blue Laser
→ detection of form and dimensional deviations

- measurement with laser scanner
- measurement with camera

with decreasing temperatures additional lighting required

influences of thermal streaks
- warming of environment
- gradient of refractive index

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5 Industry 4.0 – Relevance for Forging Industry
Process Monitoring

Measurement of Hot Forgings

Conclusions (performed study)

- scanner systems with blue laser suitable for measuring red-hot forgings (based on laser triangulation)

- accuracy requirements can be guaranteed within large temperature range if $\vartheta > 950 \, ^\circ\text{C}$:
  - occurrence of physical effects (generation of thermal streaks)
  - influencing of measuring results
  - minimization possible (based on suitable correction algorithm)

- Furthermore
  - suitability of camera systems for measuring of hot forgings proven (2D system was used in finished study)
  - next step: evaluation of 3D camera systems regarding utilizability
5 Industry 4.0 – Relevance for Forging Industry
Intelligent, Flexible Manufacturing Structures

Initial Situation

Socio-Technical System

Technology

Step 1 Organization

Step n

Human

work task

rigid (inflexible) man-machine-interaction

disturbances, changing boundary conditions and demands…

Robustness ?

Modification effort ?

Ability to respond ?
5 Industry 4.0 – Relevance for Forging Industry
Intelligent, Flexible Manufacturing Structures

New Demand

decentralized adaption, partially autonomous
5 Industry 4.0 – Relevance for Forging Industry
Intelligent, Flexible Manufacturing Structures

Example: Process Route for Hollow Gearshafts (forming-based)

Intelligent, flexible, self-organizing processes and process chains

Challenges
crosslinking, monitoring, closed-loop control of
- manufacturing process / systems
- logistic processes
- transport systems

Foci
Æ "qualification" of single steps / entire process route
Æ development and adaption of interfaces, monitoring / closed-loop control strategies (data acquisition, transfer, processing)
Æ adaption / optimization of work organization / process design
Æ proof of process capability

Target: efficiency (costs, energy, resources), quality, part characteristics, lead time, load factor, ...
5 Industry 4.0 – Relevance for Forging Industry
Intelligent, Flexible Manufacturing Structures

Future Implementation of Industry 4.0 Measures into Forging Industry (especially SMEs)

Barriers / Restraints

- **scepticism** about benefits (management, staff)
  - limited human resources
  - complex, hardly tangible topic
  - measure implementation connected with effort

- **production condition** in forging plants

definition of **real objectives**
accessible with **manageable effort**
(considering local conditions)