Designing new damage tolerant forging steels by ICMPE

Wolfgang Bleck

Outline
Topics
Steels
Trends
Outline

Topics
- New processes
- Optimal material utilisation
- Damage tolerance
- Integrated Computational Materials Engineering (ICME)
- Nano-characterisation

Steels

Trends

Topics: new processes
**Topics: new processes**

- Conventional process chain
- EcoForge process chain
- **PHFP-Mod. process chain**

**Steps in the process chain**:
- Austenitisation
- Forging
- Controlled cooling
- Isothermal holding
- Surface treatment
- Machining at medium heat
- Air cooling
- Machining at medium heat

**Heating**

**Time (t)**
**Topics: new processes**

- Conventional process chain
- EcoForge process chain
- PHFP-Mod. process chain
- High temperature carburising process chain

- Austenitisation
- Forging
- Hardening
- Carburising

**Topics: material utilisation**

- High pressure components
- Gear components

Source: Bosch, Schaeffler
**Topics: material utilisation**

**High pressure components**

Conventional 100Cr6 as bainite

Source: DVM-Bericht 135 "Optimierungspotentiale in der Betriebsfestigkeit", Sindelfingen 2008

Source: Bosch, Schaeffler

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**Topics: material utilisation**

**Cylinder roller bearing NU 1010**

**Gear components**

Relative capacity:

Source: Bosch, Schaeffler
**Topics: damage tolerance**

![Diagram showing load and load capacity with safety and ppm-failure](source: HiPerComp)

- Increased damage tolerance
- \( \sigma_2 < \sigma_1 \)

**Source:** HiPerComp

Steels: Q&T steels

Transformation of retained Austenite into Martensite in front of a fatigue crack:

EBSD picture of a crack tip of a TRIP 780: Ferrite and Martensite are red, retained Austenite is green [1]

Volume fraction of retained Austenite as a function of distance from crack tip measured by EBSD [2]


Topics: ICMPE Integrative Computational Materials and Process Engineering
Thermodynamic databases

Comprehensive, standardised, modular and extendable modeling platform being efficiently adaptable to a specific material, process-chain and product

Topics: ICMPE
Integrative Computational Materials and Process Engineering

Hot rolling  Forging  FP annealing  Machining  Carburising

AixVIPMaP© – Aix (Aachen)
Virtual Platform for Material Processing
**Topics: nano-characterisation**

- **1 m**
- **10^-3 mm**
- **10^-6 µm**
- **10^-9 nm**

Nanostructured steels

- **Ultra Fine Grain (UFG)**
- **Thermo Mechanically Processed (TMP)**
- **conventional steel**

Source: Müller Weingarten AG

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- Optimal material utilisation
- Damage tolerance
- Integrated Computational Materials Engineering (ICME)
- Nano-characterisation

Steels
- Case-hardening steels
- Quenched and Tempered Steels
- Bearing steels
- High Mn steels

Trends

Steels: Case hardening steels
Steels: Case hardening steels

High temperature carburizing decreases the production time and costs of gear components.

Grain size control of austenite is needed.

Grain growth can be prevented by microalloying of case hardening steels.

Prediction and optimization of particle size and amount is performed by numerical simulation of particle evolution.
### Steels: Al-free steel

**120 ppm N**

1. MLE (C,N)
2. MnS
3. AlN

**220 ppm N**

1. MLE (C,N)
2. MnS
3. AlN

---

**Steels: Al-free steel**

- **Casting**
  - CASTS carburising
- **Hot rolling**
- **Forging**
- **FP Annealing**
- **Machining**
- **Carburising**

**Grain growth**

- **Normal grain growth**
- **Abnormal grain growth**

**Zener pinning pressure, MPa**

- **Initial grain size, um**

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Designing new forging steels by ICMPE - Wolfgang Bleck
AI reduction is requested for cleanliness improvement. The same pinning force at 1050 °C in Nb modified 25CrMo4 steel can be obtained by an increase of Nb content to 850 ppm. Additionally, an increase in solution temperature is needed. Conclusion: a combined development of alloy and process parameters is needed in order to realize this new steel concept.

Steels: Al-free steel

<table>
<thead>
<tr>
<th>REF</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Cr</th>
<th>Mo</th>
<th>Ni</th>
<th>V</th>
<th>Al</th>
<th>Nb</th>
<th>Ti</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al-free</td>
<td>0.24</td>
<td>0.22</td>
<td>0.90</td>
<td>0.92</td>
<td>0.42</td>
<td>0.18</td>
<td>0.18</td>
<td>0.008</td>
<td>0.034</td>
<td>0.0090</td>
<td>0.0170</td>
</tr>
</tbody>
</table>

References
Steels: Quenched & Tempered steel

**PHFP-M = Precipitation Hardening Ferritic-Pearlitic - Modified**

- PHFP-M: pearlite lamellae spacing $\lambda$
- Ti, V, Nb (C,N): ferrite fraction

**Steels: Quenched & Tempered steels**

**HDB = High Strength Ductile Bainitic**

- HDB: bainitic ferrite $F_p$ + retained austenite
- PHFP-M: pearlite lamellae spacing $\lambda$
- Ti, V, Nb (C,N): ferrite fraction
Bainitic steels: Phase field simulation

Kinetics calculations and microstructure evolution simulations

Phase-field simulated bainitic sheaves

SEM observation of bainitic sheaves

Bainitic steels: Phase field simulation of precipitates
Microstructural description of bainite

<table>
<thead>
<tr>
<th>Basic structure (LOM)</th>
<th>Sub structures (sLOM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystal structure</td>
<td>Form</td>
</tr>
<tr>
<td>Polygonal$^1$</td>
<td>Boundary</td>
</tr>
<tr>
<td>Quasi-Polygonal$^1$</td>
<td>Intragranular</td>
</tr>
<tr>
<td>Granular</td>
<td></td>
</tr>
<tr>
<td>Widmanstätten</td>
<td></td>
</tr>
<tr>
<td>Acicular</td>
<td></td>
</tr>
<tr>
<td>Lath-like$^2$</td>
<td></td>
</tr>
<tr>
<td>bcc</td>
<td></td>
</tr>
<tr>
<td>Location</td>
<td>2nd phase</td>
</tr>
<tr>
<td></td>
<td>2nd phase form</td>
</tr>
</tbody>
</table>

Definitions:
$^1$Roundness (Diff. of enclosing/enclosed ellipse)
$^2$Aspect ratio (Length/Width)

Microstructure characterisation by SEM

<table>
<thead>
<tr>
<th>Primärphase</th>
<th>Sekundärphase</th>
</tr>
</thead>
<tbody>
<tr>
<td>kristallographische Struktur</td>
<td>Morphologie</td>
</tr>
<tr>
<td>krz (Ferrit)</td>
<td>Polygonal</td>
</tr>
<tr>
<td>Quasi-polygonal</td>
<td>Infragranular</td>
</tr>
<tr>
<td>Widmanstätten</td>
<td>Lattenartig</td>
</tr>
<tr>
<td>Acicular</td>
<td>Blockartig</td>
</tr>
</tbody>
</table>

TRIP1 $T_\text{iso}=375°C$ $t_\text{iso}=30 min$ 4000-fache Vergrößerung

Steels: bearing steels

**ab initio Modelling**

Source: Schaeffler

Mechanical properties and microstructures in 100Cr6

**Mechanical properties**
- High tensile strength (> 2 GPa)
- High hardness (> 700HV)
- Fatigue strength
- Wear resistance
- Ductility
- Toughness
- ......

**Microstructure**
- Martensitic matrix + precipitates
- Bainitic ferrite matrix + precipitates
- Types
- Vol. fractions
- Morphology
- Strain energy
- Bound./matrix
3-Dimensional Atom Probe approach – Sample preparation

- Electropolishing + FIB sharpening
- FIB Lift-out + TEM + FIB resharpening

Atom Probe Tomography: sample and results
APT results: Precipitates in lower bainite

Carbon atom map and 13 at% isoconcentration surface in lower bainite in 100Cr6 isothermally heat treated at 260 °C for 2500 s.

Bearing steel 100Cr6: carbide analysis in bainitic matrix

ε and θ carbides in ferrite have almost identical thermodynamic stability. In austenite, however, cementite formation is clearly preferred. This indicates that ε carbide is more prone to precipitation from lower bainite than from upper bainite.

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**Processing of forging steels: cooling strategy**

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1: Forging</td>
<td></td>
</tr>
<tr>
<td>2: Dependent on component size: acceleration of cooling by fan</td>
<td></td>
</tr>
<tr>
<td>3: Isothermal transformation step $T_{iso} = 375^\circ C$ für 15 Minuten</td>
<td></td>
</tr>
<tr>
<td>4: Quenching in water</td>
<td></td>
</tr>
</tbody>
</table>

**Industrial tests**

- Inhomogeneous cooling in different component areas impedes homogeneous microstructure development. Processing adjustments dependent on size and geometry are required.
**Forging steels**

<table>
<thead>
<tr>
<th></th>
<th>Av at RT in J</th>
<th>Rp0,2 in MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>AFP</td>
<td>20</td>
<td>600</td>
</tr>
<tr>
<td>AFP-M</td>
<td>30</td>
<td>700</td>
</tr>
<tr>
<td>Q + T</td>
<td>40</td>
<td>800</td>
</tr>
</tbody>
</table>

**Automotive applications:**

- Steering Link: ~ 1 kg
- Common Rail: ~ 2 kg
- Axle Leg: ~ 5 kg

**Steels: Q&T steels**

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>S</th>
<th>Cr</th>
<th>Mo</th>
<th>B</th>
<th>Nb</th>
<th>Ti</th>
<th>V</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>42CrMo4</td>
<td>0.440</td>
<td>0.30</td>
<td>0.80</td>
<td>0.022</td>
<td>1.15</td>
<td>0.190</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>AFP-M</td>
<td>0.360</td>
<td>0.68</td>
<td>1.44</td>
<td>0.026</td>
<td>0.15</td>
<td>0.030</td>
<td>-</td>
<td>0.029</td>
<td>0.022</td>
<td>0.19</td>
<td>0.0210</td>
</tr>
<tr>
<td>HDB</td>
<td>0.226</td>
<td>1.62</td>
<td>1.50</td>
<td>0.019</td>
<td>1.30</td>
<td>0.079</td>
<td>0.0030</td>
<td>0.030</td>
<td>0.024</td>
<td>-</td>
<td>0.0105</td>
</tr>
<tr>
<td>TRIP</td>
<td>0.181</td>
<td>0.97</td>
<td>2.50</td>
<td>0.017</td>
<td>0.20</td>
<td>0.096</td>
<td>0.0018</td>
<td>-</td>
<td>0.032</td>
<td>-</td>
<td>0.0069</td>
</tr>
</tbody>
</table>

**Chemical composition in mass-%**

- **42CrMo4**: 0.440 C, 0.30 Si, 0.80 Mn, 0.022 S, 1.15 Cr, 0.190 Mo, - B, - Nb, - Ti, - V, - N
- **AFP-M**: 0.360 C, 0.68 Si, 1.44 Mn, 0.026 S, 0.15 Cr, 0.030 Mo, - B, 0.029 Nb, 0.022 Ti, 0.19 V, 0.0210 N
- **HDB**: 0.226 C, 1.62 Si, 1.50 Mn, 0.019 S, 1.30 Cr, 0.079 Mo, 0.0030 B, 0.030 Nb, 0.024 Ti, - V, 0.0105 N
- **TRIP**: 0.181 C, 0.97 Si, 2.50 Mn, 0.017 S, 0.20 Cr, 0.096 Mo, 0.0018 B, - Nb, 0.032 Ti, - V, 0.0069 N

**Designing new forging steels by ICMPE - Wolfgang Bleck**
Forging steels

- AFP
- AFP-M
- Q + T
- HDB
- +micro-alloying elements
- +bainitic microstructure

Forging steels

- AFP
- AFP-M
- Q + T
- TRIP
- HDB
- +retained austenite in bainitic microstructure
- +bainitic microstructure
- +micro-alloying elements
Forging steels with TRIP - effect

Austenite stability

Intrinsic Parameters:
- Chemical Composition
  - C: increases γ stability
  - Si: solid solution strengthening; carbide formation retarded
- Morphology
  - Film-like austenite parallel to bainite sheaves shows slower transformation
- Size
  - Austenite grains <0.01 µm are very stable
- Crystallographic Orientation

Extrinsic Parameters:
- Location of austenite grains
  - Different C enrichment dependent on diffusion conditions
- Hardness of matrix
  - High hardnes impairs transformation due to volume change
- Stress state
  - Kinetic of transformation depends on stress state
- Residual stresses


Static and cyclic properties of Q+T steels and TRIP steels

- Static tensile properties Q+T > TRIP
- Cyclic properties Q+T < TRIP (constant loading)
- Cyclic properties Q+T < TRIP (variable loading)
  - Service fatigue life of TRIP forging steel is improved compared to conventional Q+T steel
### Notch sensitivity

\[ \text{Formzahl } K_i = \frac{\sigma_{t,\text{max}}}{\sigma_n} \]

- Smaller notch sensitivity of TRIP steel compared to Q+T steels
- Notch sensitivity of TRIP comparable to mild steels
- Advantages for components with complex geometrical shapes

### Outline

#### Topics
- New processes
- Optimal material utilisation
- Damage tolerance
- Integrated Computational Materials Engineering (ICME)
- Nano-characterisation

#### Steels
- Case-hardening steels
- Quenched and Tempered Steels
- Bearing steels
- High Mn Steels

#### Trends
High Mn Steels: Mechanical properties and deformation modes

Deformation Mechanisms in High Manganese Steels

SLIP: Dislocation slip
TRIP: Transformation induced plasticity
TWIP: Twinning induced plasticity
MBIP: Microband induced plasticity
Material design

Deformation Twins

- Before cold rolling
- After cold rolling
- After recovery annealing

### Material design

![Graph showing variation of rolling degree and annealing parameters](image)

Variation of rolling degree and annealing parameters allows the adjustment of final mechanical properties.

**CR:** cold rolled  **RC:** recovered  **RX:** recrystallized


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### In situ bending test in large chamber SEM

**Crack initiation at characteristic microstructural features**

- Twins and twin intersections are visible
- Surface roughening
- Fracture occurs on surface at shear bands

![Image of crack initiation and microstructural features](image)

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53 54
Investigation of surface defects by confocal microscopy I

Steel: X60Mn17

Damage development

Investigation of H effects in AHHS

Damage related to Hydrogen — Identification of hydrogen related mechanisms in steels

$H\Psi = E\Psi$
### Nanostructured Steels Stähle

#### Process
- Transformation + precipitation
- Twinning during deformation
- Transformation during deformation
-渠道 by intermetallics

#### Interfaces
- SLIP
- TRIP
- MBIP
- MMnS
- α’ retained γ

**SLIP**: Dislocation slip  **TRIP**: Transformation induced plasticity  **TWIP**: Twinning induced plasticity  **MBIP**: Microband induced plasticity  **MMnS**: Mittel-Mn-Stähle

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#### Trends
- ICMPE
- Damage tolerant design
- Nanostructuring
Trends: ICMPE

Integrative Computational Material and Process Engineering

- Hot rolling
- Forging
- FP annealing
- Machining
- Carburising

Integration of machining

Thermodynamic databases

Standardised data format / data generation ab initio

AixViPMaP

Trends: damage tolerance

Damage prevention approach:
Avoid any damage occurrence by local stress / strain accumulation that results in local failure

Damage tolerance approach:
Allow local metal degradation but limit its impact on the component structural behavior

Self healing approach:
Allow local metal degradation but enable inherent repair

Avoid critical features
Accept local plasticity
Allow diffusion repair
**Steels: bearing steels**

![Diagram showing the distribution of elements in steels](image)

Cr atoms map ~12nm

**Trends: Nanostructuring**

1-Dimensional concentration profile showing the distribution of C, Si, Cr, Mn in undissolved spheroidized carbide (Fe,Cr)$_3$C, newly formed cementite at 500 °C and bainitic ferrite matrix.

- Cr exhibits a gradual chemical gradient from surface to the core in spheroidized carbides.
- Si exhibits a large enrichment at the growth front of cementite, which hinders the coarsening of cementite particles.
- The spheroidized carbide may exist as a nucleation site for the precipitation of cementite within bainite.
- This microstructural feature might be beneficial for wear resistance and fatigue properties of the material.
Acknowledgement

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