RELATIONSHIPS BETWEEN MICROSTRUCTURE AND MECHANICAL PROPERTIES OF AUTOMOTIVE SHEET STEELS

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Faculty of Mechanical Engineering
Faculty of Mechanical Engineering

- Institute of Engineering Materials and Biomaterials
- Institute of Technological Processes Automation and Integrated Manufacturing System
- Institute of Computational Mechanics and Engineering
- Institute of Fundamentals of Machinery Design
- Department of Theoretical and Applied Mechanics
- Department of Welding Engineering
- Department of Machine Technology
- Department of Foundry Engineering
LASER WELDING AND SURFACING

RESEARCH TASKS

1. Laser welding
2. Laser surfacing
3. Laser alloying
4. Laser surface heat treatment

CONTACT PERSON: Prof. Jacek Górka
NUMERICAL SIMULATIONS OF WELDING and HEAT TREATMENT PROCESSES

RESEARCH TASKS
1. Residual stresses and distortions distribution analyses
2. Fatigue prediction
3. Cracking prediction
4. Optimization of welding processes and weding repairs technologies

CONTACT PERSON:
Prof. Jacek Górka
Faculty of Mechanical Engineering

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- Department of Machine Technology
- Department of Foundry Engineering
Since 2011 I have been an associate professor in the Institute of Engineering Materials and Biomaterials at the Faculty of Mechanical Engineering.

1 full professor
20 associate professors
50 assistant professors
30 PhD students

My topics:

Materials:
High strength low-alloyed steels – HSLA
I Generation AHSS – DP, TRIP, CP
II Generation AHSS – high-Mn
III Generation AHSS – medium-Mn

Processes:
Hot deformation
Thermomechanical processing
Phase transformations
Weldability
Corrosion resistance
1st, 2nd and 3rd generation of automotive sheet steels - AHSS
Thermomechanical processing
Heat treatment
Sintered metallurgy
Surface engineering and PVD / CVD coatings
Magnesium alloys
Aluminium alloys
Copper alloys
Sintered stainless steels
Metallic, polymer and ceramic composites
Severe plastic deformation of lightweight alloys
Nanotubes
Corrosion resistance
Biomaterials
Selective Laser Melting - Lightweight concepts and moulds with conformal channels

RESEARCH TASKS
1. Aluminum or titanium lightweight structures
2. Porous structures
3. Polymer-metal composites
4. Topology optimization
5. Optimising the thermal performance of moulds
6. Analysis of thermal cooling

CONTACT PERSON: Mariusz Król Ph.D. Eng.
Conventional Metallurgical Processing under Laboratory Conditions

RESEARCH TASKS

1. Complex Automotive Aluminum Cast Components
2. Analysis of the micro/macro segregation effect on alloy and cast component performance
3. Analysis of the characteristic temperatures of metallurgical reactions
4. Optimization of the heat treatment process conditions including elimination of segregation

CONTACT PERSON: Mariusz Król Ph.D. Eng.
Functional materials and recycling

RESEARCH TASKS

Advanced amorphous materials (metallic glasses),
  • amorphous – crystalline gradient material (A-CGM),
Magnetic amorphous materials,
  • ferromagnetic metallic glasses for shielding of electromagnetic fields in electric cars,
Composite materials with polymeric, metallic and ceramic matrix;
  • functional composite materials (without halide e.g. Cl) for the protection of fire spreading in car components,

Determination of production problems investigation procedures,
  • identification of quality problems,

Materials and environment
  • Circular Economy aspects in automotive multimaterial parts design,
  • planning and design of materials including their recycling,
  • application in the automotive industry materials from recycling

CONTACT PERSON: Piotr Sakiewicz Ph.D. Eng.
1. INTRODUCTION
2. I GENERATION AHSS
3. II GENERATION AHSS
4. III GENERATION AHSS
5. WELDABILITY OF AHSS
6. CONCLUSIONS
The average tensile strength of the steel used in a typical car increases.

Continuous competition between steel, aluminium, magnesium and polymer materials.

Driving force of development.

• **CRUMPLE ZONE** – its aim is energy absorption.

• **SAFETY CAGE** – its aim is to maintain a survival space.

• **CLOSURE ELEMENTS** – aesthetic functions.

Source: www.mercedesclass.net
MATERIAL SELECTION

CLOSURE
ENERGY
ABSORPTION
ANTI-INTRUSION PARTS

Source: www.mercedesclass.net

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10 IV 2018, Gliwice, Poland
APPLICATION OF MULTIPHASE STEELS

Body-in-white of Porshe Cayenne

Steel material types:
- DP600
- CPW900
- ZStE380
- Trip700

Source: www.autosteel.org
Seminar on Great Designs in Steel, Mehrkens, 2004
1. INTRODUCTION
2. I GENERATION AHSS
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ADVANCED HIGH-STRENGTH STEELS (1 GENERATION AHSS)

Features:

• strength increases and ductility decreases with increasing volume fraction of hard phases, i.e. martensite or bainite
• high work hardening in DP steels by martensitic islands
• high work hardening in TRIP steels by strain-induced martensitic transformation of retained austenite

Combination of soft and hard phases – composite-like behavior
• **hot-rolled sheets**: a multi-step cooling from a finishing rolling temperature

• **cold-rolled sheets**: intercritical annealing using a continuous annealing line (CAL) after cold rolling – with zinc coatings / without galvanizing
Low-medium-C Si-Al steel with Nb and Ti microadditions

Chemical composition of the investigated steel

<table>
<thead>
<tr>
<th>Mass content, wt. %</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
</tr>
<tr>
<td>0.24</td>
</tr>
</tbody>
</table>

Important:
- partial substitution of Si by Al
- steel contains microadditions of Nb and Ti
- grain refinement and precipitation strengthening by dispersive phases of MX type
- increase of strength properties
- indirectly: decreasing grain size of retained austenite
CONTINUOUS COMPRESSION USING THE GLEEBLE 3800 THERMOMECHANICAL SIMULATOR

True strain

\[ \varepsilon = \ln \left( \frac{h_1}{h_0} \right) = 1 \]

Strain rate

0.1, 1, 10s\(^{-1}\)
Effect of Mn addition

- Flow stresses of medium-Mn steels are slightly higher compared to 1 GEN AHSS.
- Flow stresses of high-Mn steels are much higher compared to 1 GEN and 3 GEN AHSS.
- A clear peak of $\varepsilon_p$ followed by decreasing the flow stress can only be observed for high-Mn steels.
Flow stresses are higher compared to conventional C-Mn-Si and C-Mn-Al-Nb TRIP steels.

Effect of Mn in a range between 3 and 5% is negligible.

Effect of Nb reveals as a slight increase of flow stress.

A clear peak of $\varepsilon_p$ followed by decreasing the flow stress can only be observed at 1150°C.
MULTI-STEP COMPRESSION USING THE GLEEBLE TO SIMULATE PHYSICALLY THE HOT ROLLING OF STEEL SHEETS

<table>
<thead>
<tr>
<th>Heating</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Soaking temperature [°C]</td>
<td>Heating rate [°C/s]</td>
</tr>
<tr>
<td>1200</td>
<td>3</td>
</tr>
<tr>
<td>Soaking time [s]</td>
<td>Cooling rate to the deformation temperature [°C/s]</td>
</tr>
<tr>
<td>30</td>
<td>5</td>
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</table>

<table>
<thead>
<tr>
<th>Deformation</th>
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<tbody>
<tr>
<td>No.</td>
<td>T [°C]</td>
</tr>
<tr>
<td>1</td>
<td>1150</td>
</tr>
<tr>
<td></td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>30</td>
</tr>
<tr>
<td>2</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>multi-step</td>
</tr>
<tr>
<td></td>
<td>–</td>
</tr>
</tbody>
</table>
7-STEP COMPRESSION USING THE GLEEBLE 3800 THERMOMECHANICAL SIMULATOR

Temperature, °C vs. Time, s

- $v = 3^\circ$C/s
- $v_1 = 30^\circ$C/s
- $v_2 = 5^\circ$C/s
- $v_3 = 40^\circ$C/s
- $v_4 = 0.5^\circ$C/s

- $T_A$, $t_A$
- $T_1$
- $T_2$, $T_3$, $T_4$, $T_5$, $T_6$, $T_7$
- $T_B$, $t_B = 300s$
THE FINISHING HOT-WORKING TEMPERATURE

- $T_A = 1200^\circ C$
- $T_{FHW} = 950^\circ C$, $850^\circ C$, $750^\circ C$
- $T_{IH} = 450^\circ C$, $t_{IH} = 300$ s
- $0.5^\circ C/s$
- $30^\circ C/s$
- $5^\circ C/s$
- $40^\circ C/s$

3Mn, 3MnNb steels
Flow stresses of medium-Mn are much higher than those for HSLA steel
The finishing deformation temperature has a crucial effect on flow stress, which attains the value of 250 MPa for the final compression step for $T_{FWH} = 950^\circ C$ and they are near twice higher when the final deformation temperature decreases to $750^\circ C$

Dynamic recovery is a process controlling work-hardening, and as a result the level of flow stress, for the overall temperature range of hot-working

The strain accumulation occurs at 750 and $850^\circ C$ whereas only slight strain accumulation occurs for a finishing hot-working temperature of $950^\circ C$ due to a much faster recrystallization progress
Structures obtained after cooling the specimens from the deformation temperature of 900°C at a rate of:

a) 61°C/s, b) 20°C/s, c) 7°C/s and d) 4°C/s
Retained austenite as irregular grains and interlath regions located in bainitic islands
An orientation map colour coded for the crystal direction parallel to the normal direction of the specimen (a), marked regions of retained austenite (b), an IQ map with low-angle and high-angle boundaries (c)

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10 IV 2018, Gliwice, Poland
Layers of retained austenite located between bainitic ferrite laths of high dislocation density

Bainitic steel

Bainitic-ferritic steel
Strain-induced martensitic transformation of retained austenite:

- High work hardening
- Delayed necking during cold deformation

High value of instantaneous work hardening exponent $n^*$

High value of uniform elongation (susceptible to drawing)

\[
\sigma = k\varepsilon^{n^*}
\]

\[
n^* = \frac{d(ln \sigma)}{d(ln \varepsilon)}
\]
Usually boundary regions of retained austenite remain untransformed
### MECHANICAL PROPERTIES

<table>
<thead>
<tr>
<th>Steel</th>
<th>Thermal route</th>
<th>YS_{0.2}, [MPa]</th>
<th>UTS, [MPa]</th>
<th>TEI (A_{50}), [%]</th>
<th>UEI, [%]</th>
<th>YS_{0.2}/ UTS</th>
<th>UTS•UEI, [MPa•%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5Mn-1Si-0.4Al</td>
<td>A1</td>
<td>423 ± 15</td>
<td>663 ± 19</td>
<td>23,9 ± 1,2</td>
<td>20,7 ± 0,7</td>
<td>0,64</td>
<td>13724</td>
</tr>
<tr>
<td></td>
<td>A2</td>
<td>428 ± 17</td>
<td>644 ± 25</td>
<td>14,9 ± 0,4</td>
<td>12,5 ± 0,2</td>
<td>0,66</td>
<td>8050</td>
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<tr>
<td></td>
<td>A3</td>
<td>461 ± 11</td>
<td>686 ± 23</td>
<td>24,3 ± 2,3</td>
<td>20,9 ± 1,8</td>
<td>0,67</td>
<td>14337</td>
</tr>
<tr>
<td></td>
<td>A4</td>
<td>472 ± 18</td>
<td>690 ± 21</td>
<td>19,5 ± 2,3</td>
<td>15,6 ± 1,5</td>
<td>0,68</td>
<td>10764</td>
</tr>
</tbody>
</table>

**Graphs:**
- A1
- A2
- A3
- A4
1. INTRODUCTION
2. I GENERATION AHSS
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II GENERATION OF AHSS

TRIP – TRansformation Induced Plasticity:
• when Stacking Fault Energy is between 12 and 20 mJ/m²
• partial transformation of austenite to martensite leads to high strength and good level of ductility

TWIP – TWinning Induced Plasticity:
• when Stacking Fault Energy is between 20 and 60 mJ/m²
• intense mechanical twinning leads to high ductility

Very beneficial strength-ductility balance
SUPERIOR DUCTILITY OF HIGH-Mn STEELS

STRETCHING

STAL TWIP Fe-25Mn-Si-3Al

TORSION

Source: www.autosteel.org
Seminar on Great Designs in Steel
10 IV 2018, Gliwice, Poland
<table>
<thead>
<tr>
<th>Steel type</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>Al</th>
<th>Cr</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRIP 1</td>
<td>0.02</td>
<td>17.9</td>
<td>3.2</td>
<td>2.9</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>TRIP 2</td>
<td>0.05</td>
<td>24.4</td>
<td>3.5</td>
<td>1.6</td>
<td>-</td>
<td>0.075 Ti</td>
</tr>
<tr>
<td>TRIP/TWIP</td>
<td>0.04</td>
<td>20.1</td>
<td>2.8</td>
<td>2.9</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>TWIP 1</td>
<td>0.06</td>
<td>26.0</td>
<td>3.1</td>
<td>2.9</td>
<td>-</td>
<td>0.034 Nb</td>
</tr>
<tr>
<td>TWIP 2</td>
<td>0.55</td>
<td>23.1</td>
<td>0.26</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>TWIP 3</td>
<td>0.27</td>
<td>30.0</td>
<td>0.4</td>
<td>4.5</td>
<td>4.1</td>
<td>0.06 Ni</td>
</tr>
<tr>
<td>TWIP 4</td>
<td>0.32</td>
<td>25.4</td>
<td>-</td>
<td>-</td>
<td>12.0</td>
<td>0.45 N</td>
</tr>
<tr>
<td>TRIPLEX</td>
<td>0.90</td>
<td>27.0</td>
<td>-</td>
<td>12.0</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
1. INTRODUCTION
2. I GENERATION AHSS
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III GENERATION OF AHSS

Main ideas:

Complex utilization of:
- solid solution hardening
- precipitation hardening
- grain refinement
- microalloying
- TRIP effect
- TWIP effect
- Shear band formation
- Strain aging

Especially suitable to different hardening mechanisms is …

III generation of AHSS contains a high fraction of austenite

Source: www.autosteel.org, D. Matlock, Seminar on Great Designs in Steel, 2006, Arlington
10 IV 2018, Gliwice, Poland
Chemical composition of the investigated steels

<table>
<thead>
<tr>
<th>Steel grade</th>
<th>C</th>
<th>Mn</th>
<th>Al</th>
<th>Si</th>
<th>Mo</th>
<th>Nb</th>
<th>S</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>3Mn steel</td>
<td>0.17</td>
<td>3.3</td>
<td>1.7</td>
<td>0.22</td>
<td>0.23</td>
<td>-</td>
<td>0.014</td>
<td>0.010</td>
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<tr>
<td>3MnNb steel</td>
<td>0.17</td>
<td>3.1</td>
<td>1.6</td>
<td>0.22</td>
<td>0.22</td>
<td>0.04</td>
<td>0.005</td>
<td>0.008</td>
</tr>
<tr>
<td>5Mn steel</td>
<td>0.16</td>
<td>4.7</td>
<td>1.6</td>
<td>0.20</td>
<td>0.20</td>
<td>-</td>
<td>0.004</td>
<td>0.008</td>
</tr>
<tr>
<td>5MnNb steel</td>
<td>0.17</td>
<td>5.0</td>
<td>1.5</td>
<td>0.21</td>
<td>0.20</td>
<td>0.03</td>
<td>0.005</td>
<td>0.008</td>
</tr>
</tbody>
</table>

Important:
- the same content of C, Al, Si, Mo
- various content of Mn and Nb microaddition
- Mn: austenite stabilization
- high-Al, low-Si strategy for carbide hampering
- Mo: solid solution hardening
- Nb: grain refinement and precipitation strengthening
MICROSTRUCTURE OF 3Mn STEELS

a) 3Mn-1.5Al-0.2Si-0.2Mo;  \( T_B=450^\circ C \)

b) 3Mn-1.5Al-0.2Si-0.2Mo-Nb;  \( T_B=450^\circ C \)
Plate morphology of strain-induced martensite

- Formed martensite contributes to fragmentation of untransformed austenite fostering its further stabilization due to reduction of particle size.
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Innovative materials

Innovative forming methods

Joining methods

Optimisation by CAD/CAM
CONVENTIONAL LASER WELDING

- welding with one laser beam,
- the main parameter that can be changed are: maximum beam power and welding speed that determine linear energy,
- simple thermal cycle,
- high heating and cooling speeds,

Higher hardness compared to base material,
Decrease in mechanical properties of welds

Problems with projected force distribution
Twin-spot laser welding allows:

- Welding with one big weld pool,
- Re-melting of welded material,
- The heat treatment of welds directly after welding

Parameters that can be changed during twin-spot laser welding:

- linear energy,
- power distribution between beams,
- distance between beams.

- Complex thermal cycles,
- Reduction of cooling speeds
The effect of position and distance between beams on weld macrostructure

Position of beams 90°, welding speed 5m/min, distance between beams 1mm, focus 0mm

Position of beams 0°, welding speed 9m/min, distance between beams 1mm, focus 0mm
HARDNESS PROFILES OF CP STEELS

<table>
<thead>
<tr>
<th>Sample</th>
<th>FZ</th>
<th>HAZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.065 kJ/mm</td>
<td>50:50</td>
<td>365</td>
</tr>
<tr>
<td></td>
<td>60:40</td>
<td>355</td>
</tr>
<tr>
<td></td>
<td>70:30</td>
<td>350</td>
</tr>
<tr>
<td>0.090 kJ/mm</td>
<td>50:50</td>
<td>350</td>
</tr>
<tr>
<td></td>
<td>60:40</td>
<td>340</td>
</tr>
<tr>
<td></td>
<td>70:30</td>
<td>344</td>
</tr>
</tbody>
</table>
1. INTRODUCTION
2. I GENERATION AHSS
3. II GENERATION AHSS
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6. CONCLUSIONS
1. Continuous competition with Al alloys, Mg alloys and polymer composites is a driving force of the continuous development of sheet steels. The most advanced are medium-Mn steels with retained austenite.

2. Final mechanical and technological properties are microstructure-dependent. Detailed investigations using new microstructural techniques are needed to know interactions between different structural constituents.

3. Strain-induced martensitic transformation of retained austenite during forming or crash events is very beneficial.

4. Weldability, corrosion protection, crashworthiness and innovative forming processes are very important.
Thank you for your attention!