Joining challenges in automotive lightweight applications

Uwe Reisgen
Christoph Geffers
Outline

• Introduction
• Motivation
• Lightweight design and multi-material mix
• Challenges to joining technology
• Composite design and multi-material mix in production
• Summary
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Located in the center of Aachen
Employees:
- 30 scientific staff
- 25 non-scientific staff
- 5 trainees
- 40 student assistants

Budget:
- ca. 4.5 million €
  (80% third party funds)

Space for tests and laboratory:
- ca. 2700 qm

Teaching:
- Welding and Joining Technology for Bachelor und Master students
- International welding engineer (IWE)
ISF - Welding and Joining Institute

Univ.-Prof. Dr.-Ing. U. Reisgen
- Head of Institute -

A: Arc Welding
Dipl.-Ing. K. Willms
- Head of Department -

B: Beam Welding
Dr.-Ing. S. Olschok
- Head of Department -

C: Cold Technologies
Dipl.-Ing. A. Schiebahn
- Head of Department -

Operations (R&D)

Operations (Industry)

Administration & Finance

FEF GmbH
Dipl.-Ing. C. Geffers
- Industrial Solutions & Services -

Dipl.-Kfm. (FH)
R. Löhr

Organisational Chart
- **Arc Welding**
  - Gas Metal Arc Welding
  - TIG-, Plasma-, SA-Welding
  - Surfacing
  - Robotic/Sensoric

- **Beam Welding**
  - Laser Beam Welding
  - Electron Beam Welding
  - Health and Work Safety

- **Cold Technologies**
  - Adhesive Bonding
  - Resistance Welding
  - Friction Stir Welding
  - Ultrasonic Welding
  - Simulation and Modelling
- Analysis of welding processes and optimization
- Development of cost-efficient welding processes and implementation
  - Consulting by our specialists
  - Consideration of requirements and needs of the client
  - The total manufacturing chain is considered
  - Only what the client needs ….
- Support for automation tasks
- Technology support on-site
  - During commissioning
  - During production
  - “Emergency services“
- Work-Shops
- Prototypes and pre-series
- Support in the search for competent system suppliers
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Average fleet emissions and assignment of CO2 emissions of different vehicle classes

- BMW 535i
- Audi A4 1.8 TFSI
- VW Golf 1.4 TSI
- Smart Fortwo

Share of vehicles of total CO2 emissions in the EU (2010): 23 %

EU limit value 2020, penalty payment of up to 95 €/(g km)

[BMW, VW, Daimler, BMU, RWTH]
Expectable CO$_2$ limit values until 2050

2) Memorandum of understanding, e.g. EU and G8+5 states, part of Copenhagen Accord 2009
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- Safety
- Legislation
- Comfort
- Interior trim
- Quality

Spiral of Weight

Source: Volkswagen AG, 3. VDI Fachkongress 2013
Almost \( \frac{1}{4} \) of consumption are a direct consequence of the weight.
Starting with the car body allows secondary effects in the entire vehicle

- Part- and function integration
- New materials and processes
- Cost -/weight optimization

Inversion of the Weight Spiral

- Lightweight design
- Reduced tank volume
- Lower power

Source: Volkswagen AG, 3. VDI Fachkongress 2013
Light Weight Materials

Relative part weight with equal function:

- Steel: -5% to 25% *
- Aluminum: 25%
- Magnesium: 50%
- CFRP (quasi-isotropic): 75%
- CFRP (unidirectional): 100%

Source: Volkswagen AG, Werkstoffsymposium 2012 „Prozess- und Werkstoffinnovationen in der Pulvermetallurgie“
Different Car Body Designs

Sheet monocoque design (steel)

Audi-Space-Frame (ASF) design

Composite design
(e.g. ASF® car body with steel rear part)

CFRP design

Source: Volkswagen AG, Werkstoffsymposium 2012 „Prozess- und Werkstoffinnovationen in der Pulvermetallurgie“
Materials for Future Lightweight Design Concepts

Hybrid lightweight structures

Multi-material mix

Smallest quantities

Small and medium quantities

Large-scale manufacture

Fibre composite plastics (FVK) for medium quantities

Optimised aluminium/steel composite design

Weight-optimised lightweight design for large-scale manufacturing

Source: Volkswagen AG, 3. VDI Fachkongress 2013
Steel-intensive design

Passat

In the past

St/Al composite design

Audi TT

nowadays

Functional hybrid structures

VW XL1

in future

Challenge to the joining technique

"...right material at the right place..."

Increase of multi-material design

Source: Volkswagen AG, Bad Nauheim 2014

Lightweight Design increases Application of Multi-Material Design
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Multi-Material Mix – Challenges to the Joining Technique

**Application**
- Future car body design concepts with composite design
  - Thermal load in paintwork drying processes
  - Material combination of highest-strength steels/ aluminium / magnesium/fibre-reinforced plastic materials
  - Structural crash-proof joints

**Challenges**
- Different heat expansion coefficients
- Intermetallic phases in fusion welding processes
- New surfacing combinations (coatings, lubricants, release agents)
- Increased risk of contact corrosion (potential difference aluminium / steel and also aluminium / magnesium fibre-reinforced plastic materials)

Quelle: Volkswagen AG
Rivetted with solid rivet

Self pierce rivetting (with semi-tubular rivet)

Flow drill screw (FDS), with/without predrilled hole

High-speed stud-setting
Resistance element welding

Resistance spot welding via process tapes (DeltaSpot)

CMT braze welding

Thermal direct joining

“Welding” Techniques for the Multi-Material Mix
General Limits of Rivetting:
- The quasi-static loads are below the achievable strength values of RP welding
- Two-sided accessibility
- Complementary element required
- A punching develops
- High joining forces (up to 100 kN) - heavy C-guns – large space required

Limits of semi-tubular self piercing rivetting compared to solid rivetting:
- Sheet strength values only up to max. 1000 MPa instead of 1600 MPa
- Maximally three instead of possibly four sheet layers
- High mechanical load on rivets
- Thicker sheet required on side of die
- It is impossible to join brittle cast materials
- Joining forces of up to 60 kN

Semi-tubular self piercing rivet: Damage of the fibre-reinforced material by squeeze force and process fluctuations
Source: Magna
Limits of FDS:
• Local heat flow
• Complementary element required
• Preferably from the thinner into the thicker material
• Preferably to be screwed from the softer into the harder material

Limits of Stud-Setting:
• Joint is undetachable
• Complementary element required
• Loud impulse noises during setting of studs
• Rear sheet layer must offer necessary support
• The material on the side of the setting has a max. strength of approx. 1000 MPa, the rear material can have a strength of approx. 1600 MPa
• Minimum material strength for the rear sheet of 1.5 mm in the case of steel and of 2.5 mm in the case of aluminium
• Material combination: preferably thin into thick and soft into hard

Rivtac: Fracture of the fibre-reinforced structure. Fibre-reinforced material takes in kinetic energy and causes thus the base material to deform too slowly, the consequence is risk of fracture.

Source: Magna
Limits of resistance element welding (WES):

- Two-sided accessibility
- Complementary element required
- A punching develops
- Handling safety required

Disturbing influence: Shifting of the electrodes

Source: LWF, Paderborn
**Limits of DeltaSpot:**

- Process tapes required
- Additional expenditure/costs, change of the process tapes
- Restrictions accessibility / flange width by the process tapes
- Process control with aluminium/steel joints in combination with adhesives is still a challenge

Source: Audi, Bad Nauheim 2012

Source: Fronius
**Limits**: CMT braze welding of hybrid board by Fronius and Voestalpine

- Only for production of blanks
- Steel sheet side must be galvanized
- Special edge preparation on the steel side
- Weld reinforcement
- Restricted forming property caused by weld reinforcement

Source: Fronius

1. Steel sheet, galvanised
2. Aluminium sheet
3. Filler material

Steel-aluminium hybrid blank

Source: Voest-Alpine
Past Experience in the Joining of Steel-Aluminum Dissimilar Material Joints in ISF

- During the last few years, several projects with the topic of joining steel with aluminum have been carried out.

- The focus of the research work has been put on the suitability of different aluminum filler materials (AlSi5, AlMg4,5Mn) for the joining of steel-aluminum dissimilar material joints.

<table>
<thead>
<tr>
<th>Arc processes</th>
<th>Material alloys</th>
<th>Type of joint</th>
<th>Plate thickness</th>
<th>Steel coatings</th>
<th>Mechanical parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma-MIG</td>
<td>EN AW-6016</td>
<td>Lap joint</td>
<td>0.8 mm / 1.0</td>
<td>+ZE</td>
<td>IHU</td>
</tr>
<tr>
<td>MIG</td>
<td>EN AW-5183</td>
<td>Butt joint</td>
<td>2 mm / 3 mm</td>
<td>+Ni</td>
<td>Tensile Tests</td>
</tr>
</tbody>
</table>
Challenges in thermal joining of steel aluminum dissimilar joints by using an aluminum wire

- Formation of brittle intermetallic phases due to the non-existing solubility of steel and aluminum at room temperature. The phases must not exceed 10 µm.
- Physical problems due to different melting points, expansion coefficients and thermal conductivity
  - Complex integration of the joining process into automobile production (application of flux, complex clamping devices due to distortion, …..)
  - Compared with other thermal joining processes only small range of facility
  - Determination of the formation of the intermetallic phases is, so far, only possible by using destructive testing
## Aims

<table>
<thead>
<tr>
<th>BMW AG</th>
<th>Joining of materials which are relevant in vehicle construction under practice-related boundary conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reduction of the influence of the metallurgical incompatibility in thermal joining of steel and aluminum</td>
</tr>
</tbody>
</table>

## Approach

<table>
<thead>
<tr>
<th>Testing of applications in vehicle construction by carrying out an assessment of demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower energy input by the application of controlled short-arc processes (CMT, coldArc)</td>
</tr>
<tr>
<td>Further development of low melting zinc based brazing materials for application cases (alloying elements, diameter, surface condition, coating, etc…)</td>
</tr>
</tbody>
</table>

This development is carried out within the scope of iterative processes from the fields of users of vehicle construction (application know-how), welding institute (process know-how) and wire manufacturers (material know-how).

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**Braze welding with zinc wire**
- Process-reliable joining of steel-aluminum dissimilar material joints without flux
- Development of weld geometries with mechano-technological favourable properties
- In the zone of the arc attachment point, a phase of steel, aluminum and zinc is developed which, compared with joining using an aluminum-based brazing material, is less brittle

Intermetallic phase which has been saturated with zinc (St/Al/Zn)
During the joining process, intermetallic phases are developed which detach as from a thickness of max. 5 µm and which are saturated by phases which are rich in zinc.

A ductile phase which is rich in zinc is adjoining the steel base material.
Static and Cyclic Strength Values of DX56D / EN AW-6016

**Static Strength**

\[
\sigma_{\text{stat}} = \frac{F}{A} = \frac{9700 \text{N}}{1 \text{mm} \times 35 \text{mm}} = 215.56 \text{ MPa}
\]

**Cyclic Strength**

\[
\sigma_{\text{dyn}} = \frac{F}{A} = \frac{2000 \text{N}}{1 \text{mm} \times 20 \text{mm}} = 100 \text{ MPa}
\]

Application Case

\[ R = \frac{\sigma_u}{\sigma_o} = 0 \] (tensile force)
The application of steel profiles and aluminum plates shall allow crash- and also lightweight relevant functions in a vehicle underbody.
Demonstration of the possibility of joining different materials with different thickness and surface coatings.
Finished Demonstrator Part
Application Case

Static Strength

Cyclic Strength

\[ \sigma_{\text{stat}} = \frac{F}{A} = \frac{10714 \text{ N}}{1 \text{ mm} \times 45 \text{ mm}} = 238 \text{ MPa} \]

\[ \sigma_{\text{dyn}} = \frac{F}{A} = \frac{2094 \text{ N}}{2 \text{ mm} \times 20 \text{ mm}} = 105 \text{ MPa} \]

\[ R = \frac{\sigma_u}{\sigma_o} = 0 \quad (\text{tensile force}) \]

Static and Cyclic Strength Values of DX56D / DX56D
Laser Beam Welding of Steel to Aluminum
FSW of Steel to Aluminum
New approach: thermal direct joining

**Principle induction technique**

- Metal
- Plastic
- Induction coil

**Principle resistance heating**

- Metal
- Plastic
- Electrodes

**Experimental set-up induction technique**

1. Upper sample holder (plastic part)
2. Pressing cylinder
3. Lower sample holder (metal part)
4. Induction coil

**Experimental set-up resistance heating**

- Displacement sensor
- Pressing tool
- Elektrodes
- Sample holder
- Plastic
Thermal direct joining with resistance heating
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Audi TT, Source: Audi

A: Resistance spot welding
B: MIG welding
C: Rivetting
D: Flow-Drill Screwing

High Number of Production Equipment
Audi TT:
- 6 different wall thickness values
- 4 different rivet types
- 6 different materials Al
- 6 different materials St

Through the multi-material mix, the number of successor models has more than doubled

<table>
<thead>
<tr>
<th>Technique</th>
<th>Process</th>
<th>Number per vehicle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical joining techniques</td>
<td>Rivetting</td>
<td>1615 piece</td>
</tr>
<tr>
<td></td>
<td>Clinching</td>
<td>164 piece</td>
</tr>
<tr>
<td></td>
<td>Flow-Drill-screwing</td>
<td>96 piece</td>
</tr>
<tr>
<td></td>
<td>Solid rivetting</td>
<td>229 piece</td>
</tr>
<tr>
<td>Thermal joining techniques</td>
<td>MIG welding</td>
<td>21462 mm</td>
</tr>
<tr>
<td></td>
<td>Laser welding</td>
<td>5309 mm</td>
</tr>
<tr>
<td></td>
<td>RP welding</td>
<td>1287 spots</td>
</tr>
<tr>
<td></td>
<td>MAG welding</td>
<td>809 mm</td>
</tr>
<tr>
<td></td>
<td>Stud welding</td>
<td>234 piece</td>
</tr>
<tr>
<td>Adhesive bonding</td>
<td>Adhesive bonding</td>
<td>97156 mm</td>
</tr>
</tbody>
</table>

Source: DVS BV Schwaben, Franz J. Lange
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• Lightweight design is an important key for reducing the CO₂ emissions
• The singular steel-, aluminium and FVK (fibre reinforced plastic material) design is replaced by composite design and further by hybrid concepts
• New car body concepts pose new challenges to the joining technique
• Existing joining techniques are already capable to fulfill most of the joining tasks
• The current multi-material mix/composite design requires, as far as economic considerations are concerned, a very high number of joining technologies
• Economically speaking, the number of varieties within one joining technology is also too high
• Composite design requires joining techniques for a possibly large bandwidth of joining tasks