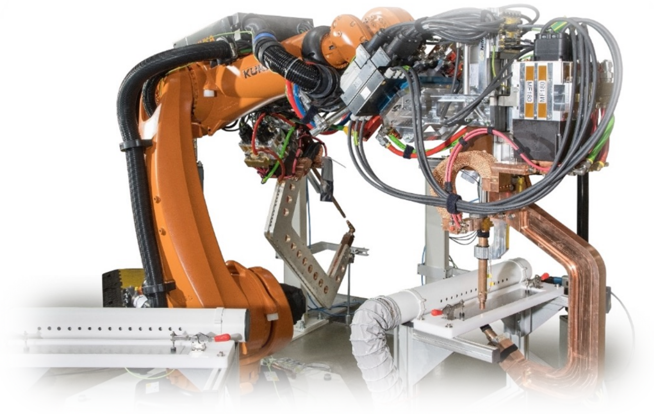
AnAttAl – Resistance Spot Welding of Aluminium Alloys:

Effects of Surface Coatings, Storage Time, and Lubrication on Weldability

Sung-Min Wi; Jiangdong Zhao; Thomas Freudenmann

Materials Testing Institute Stuttgart
Department Joining Technology and Additive Manufacturing



AnAttAl - Experimental and Simulative Analysis of Material- and Surface-Specific Attributes of High-Strength Aluminum Alloys

AnAttAI - DE: Experimentelle und simulative Analyse von material- und oberflächenspezifischen Attributen bei hochfesten Aluminiumlegierungen

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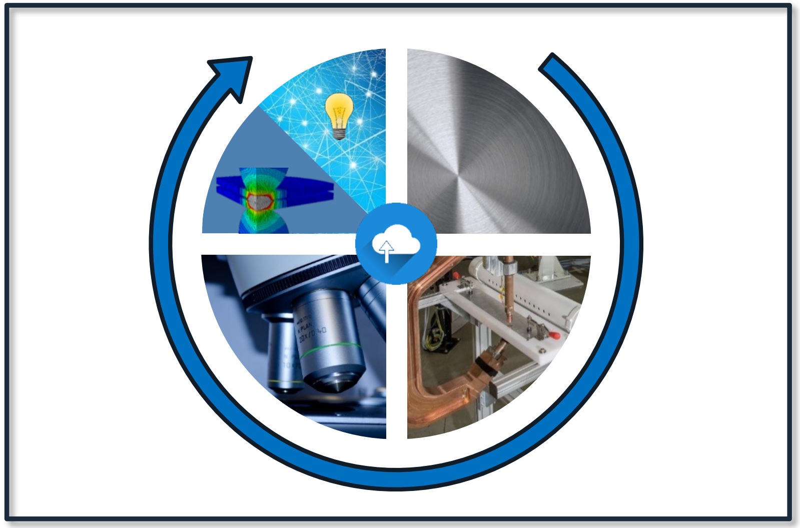

Experimental and Simulative Analysis of Material- and Surface-Specific Attributes of High-Strength Aluminum Alloys

→ *Targeted variation of material and surface properties of aluminum alloys*

→ *Ontology development and AI application*

→ *Resistance and electron beam welding*

Funded by

Bundesministerium für Bildung und Forschung

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EDI Engineering Data Intelligence

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Sur Tec

Project Lead

Mehr Infos

Project Goals - experimental

Material

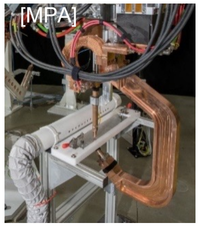

Body-In-White
(ARENA2036 University of Stuttgart)

Alumium as a Material

Lightweight construction:
Aluminum is becoming increasingly important

„The aluminum content per car is estimated to rise to around 196 kg (2025)"

Technology

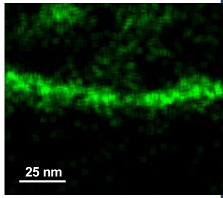


Resistance Spot Welding
(Most common Joining process in body-in-white production - Automotive)

Electron Beam Welding

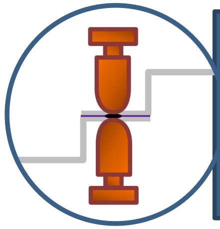
Vario Picker

Research at the MPA



Characterization

- Different analytical methods for thickness measurement were evaluated in cooperation with several institutions.
- Adhesive behavior prior to welding was examined visually → layer thickness and volume distribution were analyzed.
- Contact resistances were measured.



Process Optimization

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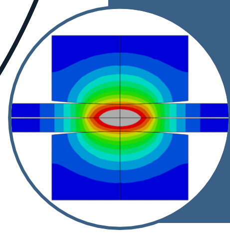
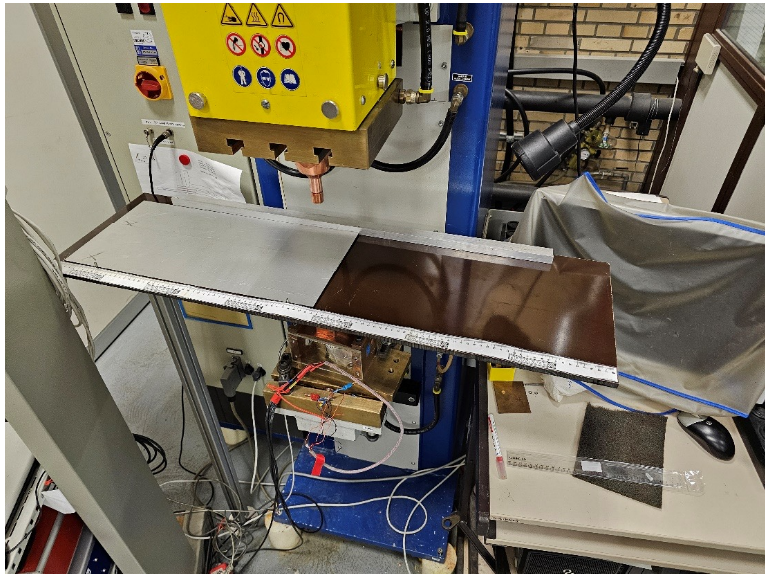


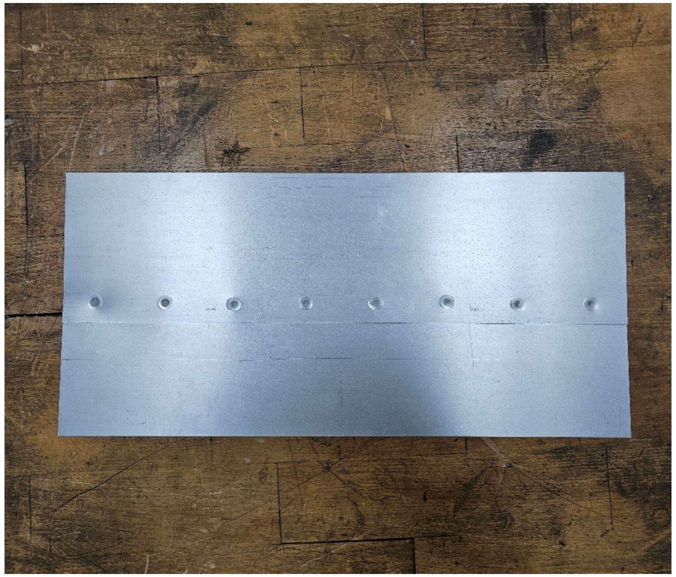
Workflow/Simulation

→ Prozessmodellierung in Abaqus
→ Kontaktmodellierung (2D-Simulation)
→ Automatisierung einzelner Schritten → in Arbeit über Pyiron-Workflow
→ Teilnahme bei PMD Workflow Hackathon

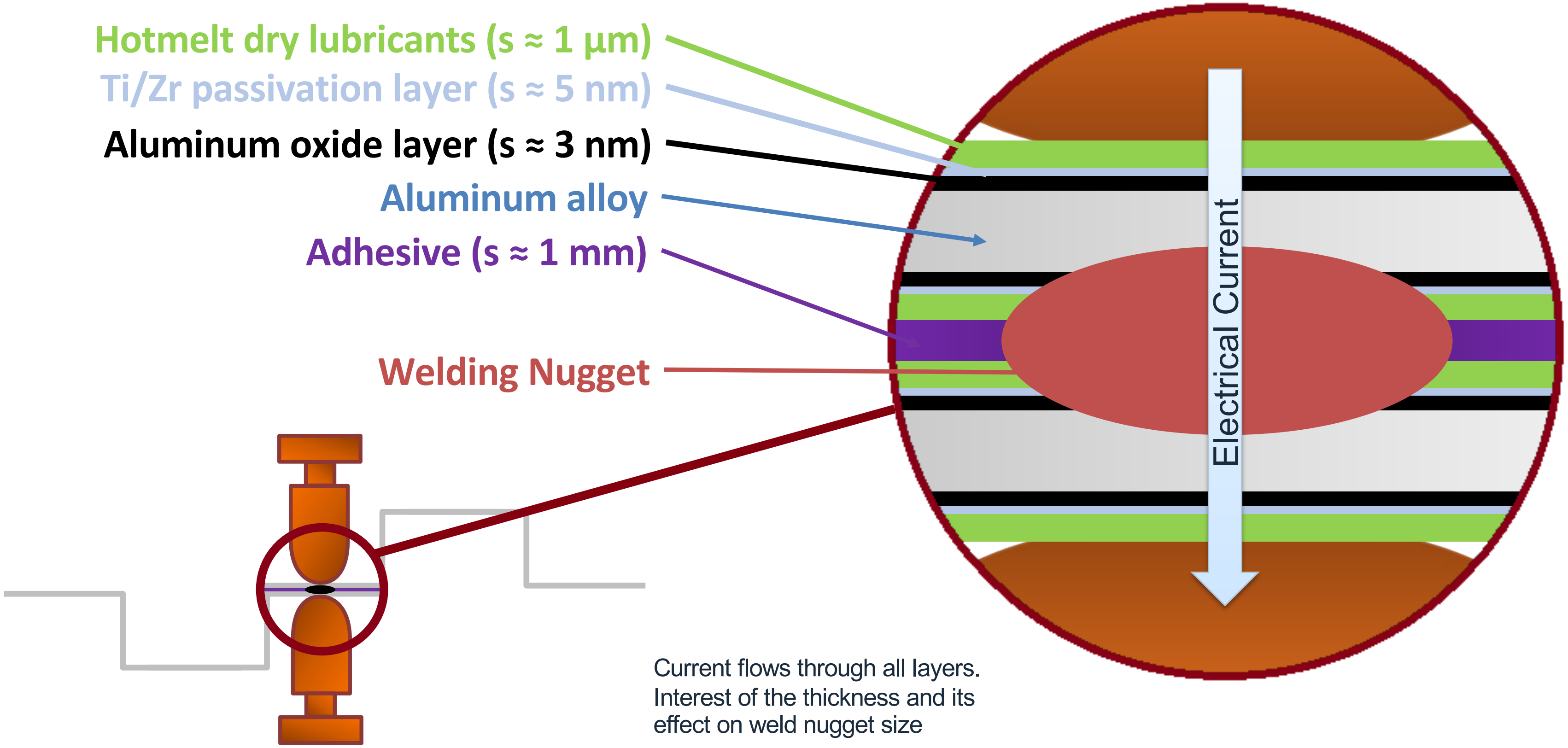
Resistance Spot Welding at MPA

Stand-alone (manual) Resistance Spot Welding station





Surface of the Aluminum Sheet – Resistance Spot Welding

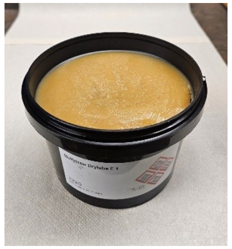


Current flows through all layers.
Interest of the thickness and its effect on weld nugget size

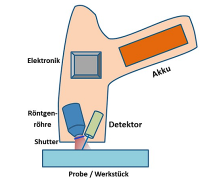
Industrial Standards

Lubricant

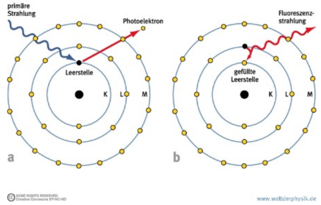
Wi - Zeller + Gmelin - Drylube E1 Hotmelt Lubricant (2025)



Passivation



https://www.fluxana.de/images/docs/DE/Leseprobe_RFA_in_der_Praxis_korrigierte_Auflage_Nr.2.pdf
(Stand: 08.12.2024)



https://www.weltderphysik.de/gebiet/teilchen/licht/synchrotronstrahlung/roentgenfluoreszenzanalyse/roentgenfluoreszenzanalyse/
(Stand: 08.12.2024)

- *Fourier-transform infrared spectroscopy*
    - IR radiation strikes the sample → specific wavelengths are absorbed. → An absorption spectrum is generated for the analysis.
    - Suitable for lubricant analysis (oil layer; C–H, C=O, O–H bonds).
    - Output in g/m² and conversion to layer thickness based on density.

- *X-ray fluorescence*
    - Atoms are excited by primary X-ray radiation, causing the emission of characteristic fluorescence. → Elemental composition is determined via energy analysis, and concentration via intensity measurement.
    - Calibration is required for each individual passivation chemistry.

Charaterization

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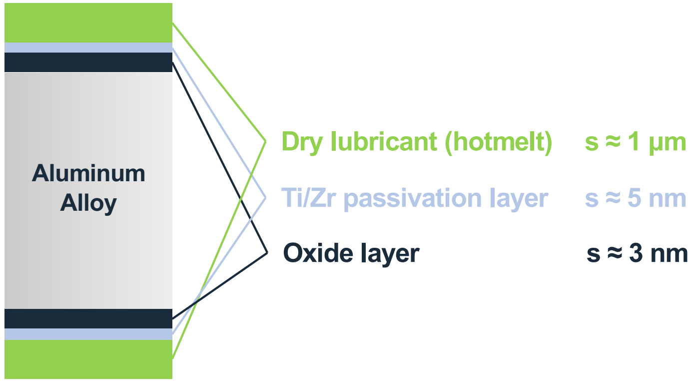
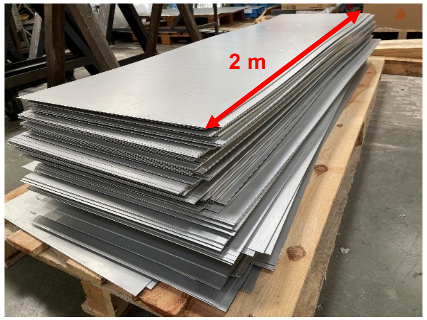
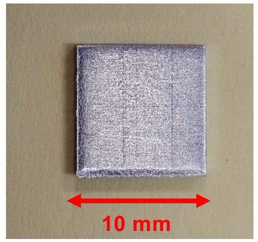
- Layer thickness measurement must be performed for each different sample batch.
- So far, no defined method exists for characterizing the passivation layer thickness.



- Regular measurement of layer thickness is too costly.
- No fast & easy or inline measurement of the passivation layer is currently possible.





- Surface roughness caused by the texture complicates the measurement.
- Reference values are needed for verification.

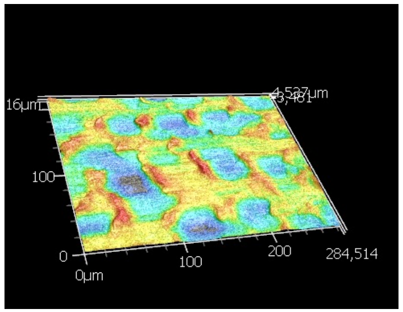
3D Profilometer & 3D Laser Scanning Microscope

- **3D Profilometer**:
  - White light; analysis of light reflection and interference for generating 3D surface profiles.
- **3D Laser Scanning Microscope:**
  - Confocal laser, focus variation, and measurement of light backscattering at each point of the sample surface to create 3D images.

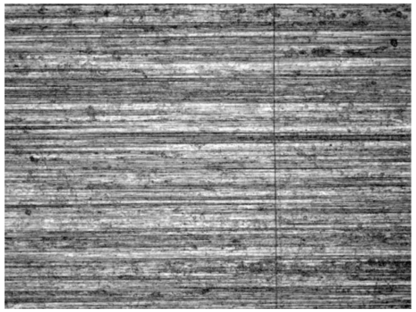
- Findings:
  - Roughness:
    - R_a around 0,6 µm
    - R_z around 3,8 µm

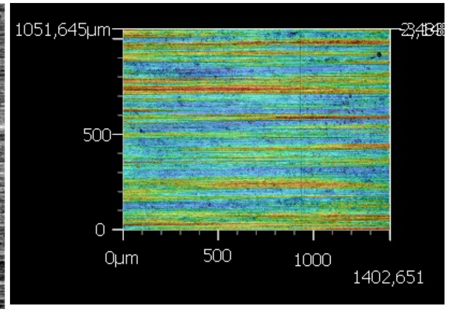
  - Topography:

Probe_2354 (EN AW 5? 6?) **EDT Texture**
KEYENCE VK-X3000 on 29.10.2024



Probe_MF (EN AW 5? 6?) MillFinish Texture
KEYENCE VK-X3000 on 29.10.2024





Surface Analysis – first results

TOF-SIMS (Time-of-Flight Secondary Ion Mass Spectrometry)	AES (Auger Electron Spectroscopy)	XPS (X-ray Photoelectron Spectroscopy)

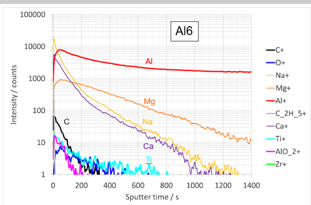
TOF-SIMS (Time-of-Flight Secondary Ion Mass Spectrometry)

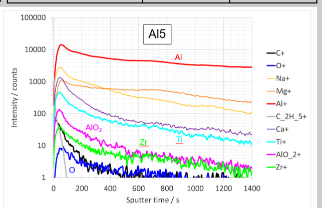
Incoming Particle: Ion Beam
Detected Signal: Secondary Ions

- **Sample Results**
  - EN AW 5182 **with** TiZr: Zr und Ti detected
  - Al6-HDI **w/o** TiZr: No Zr detectable; weak Ti-Signal (Ti in Alloy)
    - Determination of layer thickness in multilayer systems using sputtering of Molybdenum and CIGS (Copper Indium Gallium Selenide).
  - *C: Lubricant; ZrTi: Passivation; AlOx: Aluminium oxide*

Al5	C	TiZr	AlOx
Half Int Min (s)	5	13	22
Thickness (nm)	2,4	3,1	17,7

Al6	C	AlOx
Half Int Min (s)	4	14
Thickness (nm)	2,9	14,0

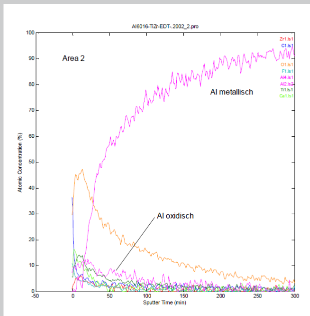




AES (Auger Electron Spectroscopy)

Incoming Particle: Electron Beam
Detected Signal: Auger Electrons

- **Sample Results**
  - EN AW 6016 with Ti/Zr
  - Layer thickness measurement:
    - Determination of sputter rates based on material-specific sputter behaviour (here: SiO_2 sputter rate used as reference → Ti/Zr corresponds to approx. 12–15 nm SiO_2)



XPS (X-ray Photoelectron Spectroscopy)

Incoming Particle: X-ray photons
Detected Signal: Photoelectrons

XPS did not provide conclusive results; only partial signals were obtained.

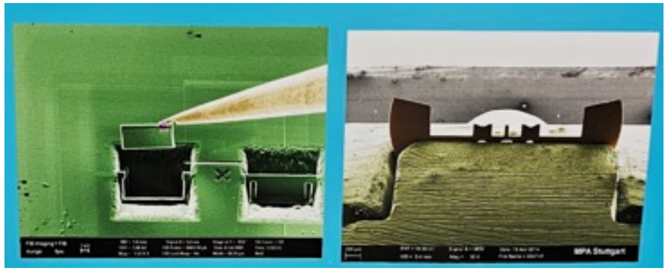
Some spectra showed only **C–O bonding**, while others indicated an **increase in the Al peak** in the survey spectrum.
→ This may be due to sputtering removing the upper atomic layers, allowing the Al signal from the passivation layer to become more prominent.

The effective information depth of XPS is **< 10 nm**.

Wolfram Hempel from ZSW Baden Württemberg on Aug. 30. 2024

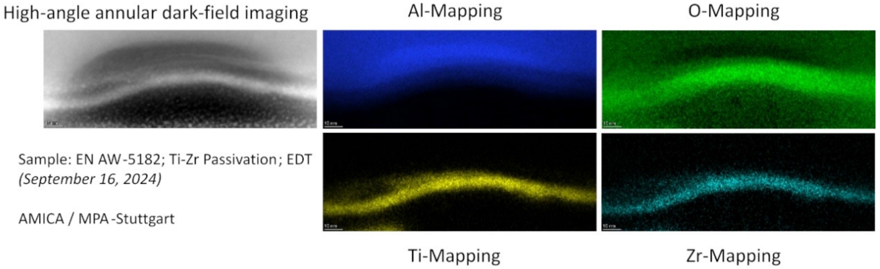
FIB-TEM

- **FIB Sample - Preparation for TEM:**
  - Cross-section created by FIB milling (100 × 100 nm)
  - A thin lamella is cut out perpendicular to the sample surface.

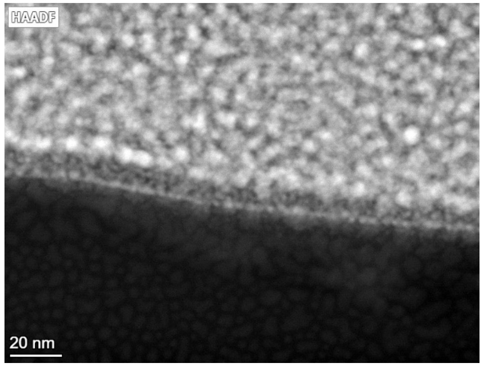


REM, TEM AMICA)

m_Ti ≈ m_Zr ≈ 4,7 mg/m² / AL5182 (EDT)



m_Ti ≈ m_Zr ≈ 4,7 mg/m² / AL1050 – Mill Finish



Summary of previous results

Analysis	Topography	Lubricant	Passivaiton layer thickness
TEM (with FIB)			Limited since roughness/texture
3D Profilometer	Yes (Roughness)		
3D Laser microscope	Yes (Roughness + Texturing)		
AFM	Yes (Roughness, small area)	limited	Maybe: Need a sample with Height Difference
XRF			Limited(4 mg/m²)
FT-IR		Yes (0,8 mg/m²)	
TOF-SIMS			Yes – need calibration (3.1 nm)
AES			Yes – need calibration (12 bis 15 nm)
LIBS			Not actually, not senstive enough.
XPS			No conclusive results now
Ellipsometry			For later maybe. Recognized the different thicknesses.

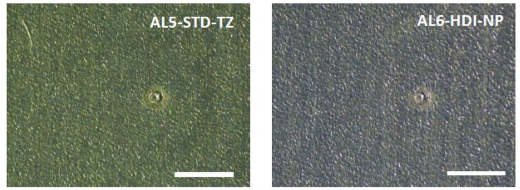
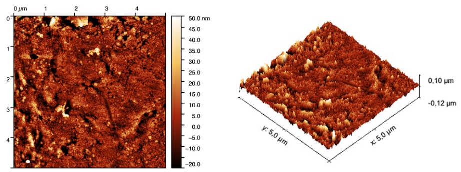


Figure 1. LIBS Spot analysis for the Sample AL5-STD-TZ and AL6-HDI-NP. The size of the bar is 2 mm.

LIBS of Lightigo 11.2024



AFM of EN AW 6016 mit Ti/Zr
Nuriye Korkmaz bei KIST Europe

Contact Resistance (RT)

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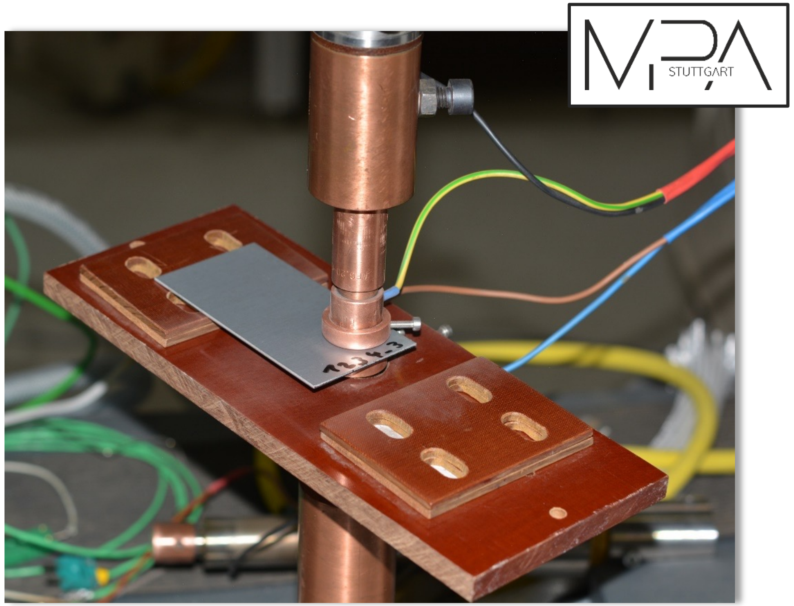
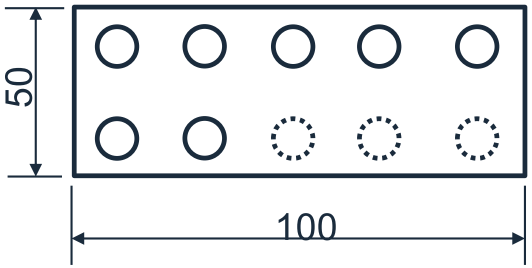
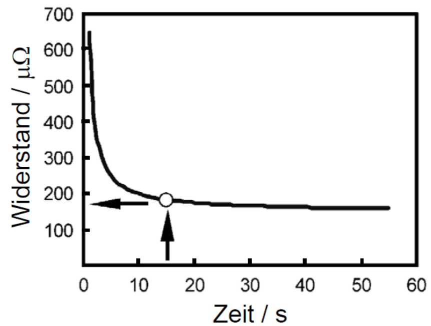




Procedure according to DVS-Merkblatt 2929-1

- (min.) 7 valid measurements per sheet
  here: 7 Measurements
- (min.) 5 sheets
  here: 5 sheets per U-Number
- Resistance value after 15 s



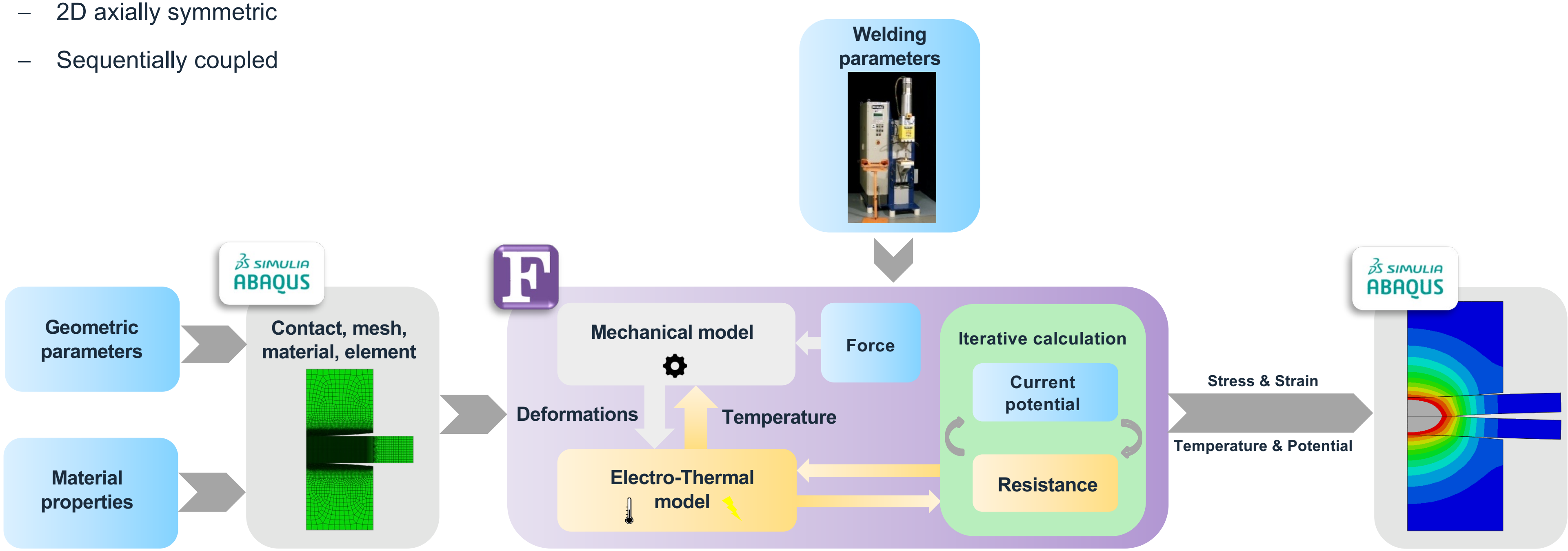
Source: DVS-Merkblatt 2929-1, 2014

I = 10 A
F = 7,5 kN } for Aluminum

Simulation Process

➢ RSW-Model in Abaqus (2018)

- 2D axially symmetric
- Sequentially coupled

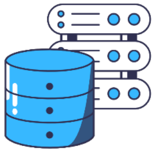


Integration with Pyiron Workflow

- In this project, Pyiron was used to automate the entire resistance spot welding (RSW) simulation chain, integrating **Abaqus**,
- **FAMOS** and several self-written **Fortran** tools into a single reproducible workflow.

1. Parameterized Pre-processing :

- Automatic update of Abaqus input files based on user's geometric requirements. Ensures reproducibility and simplifies
- parametric studies.

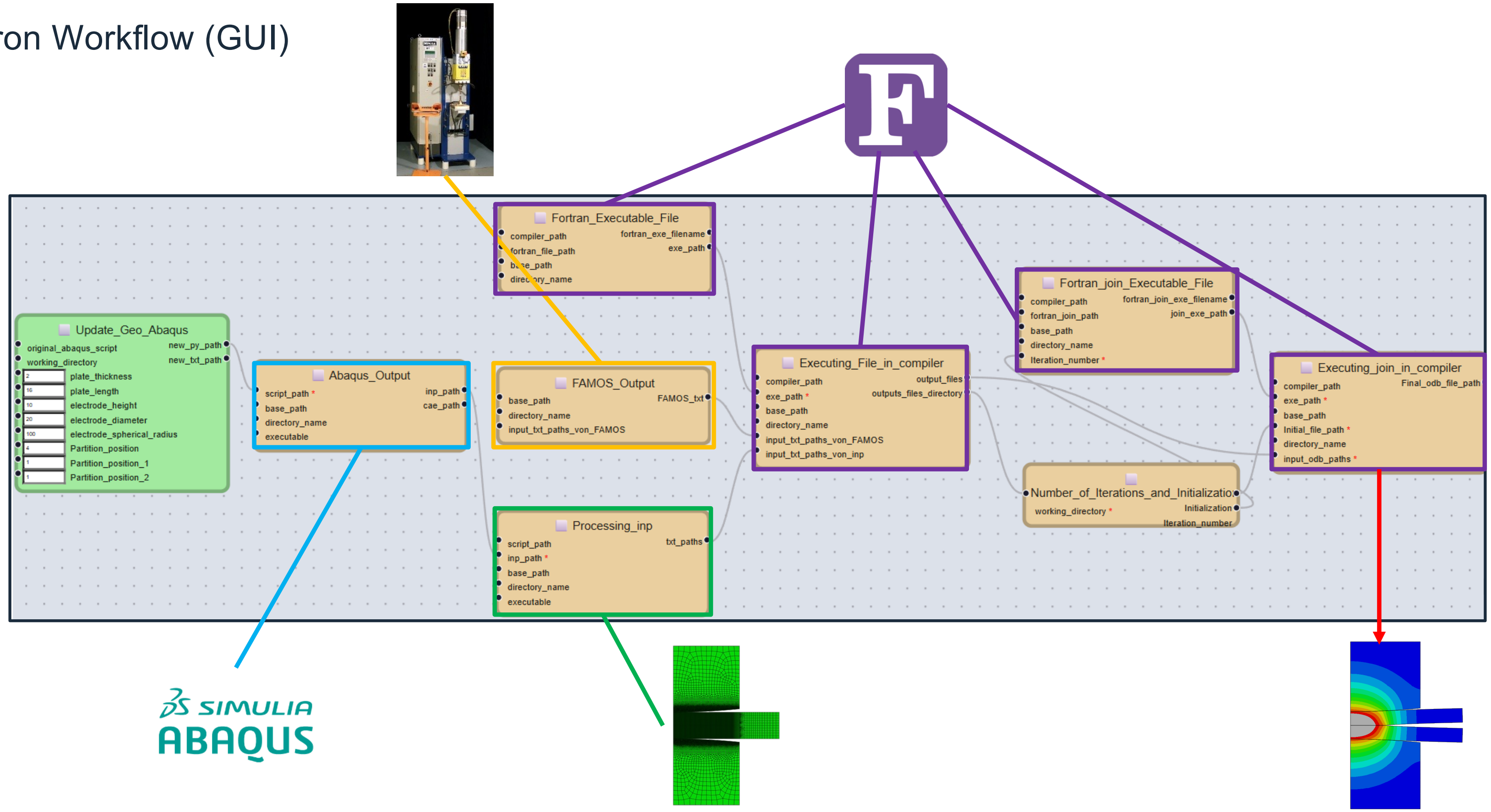


- **2. Pyiron automatically runs executables, passes file paths and handles directories:**
- This converts a normally manual, error-prone workflow into a structured automated pipeline.

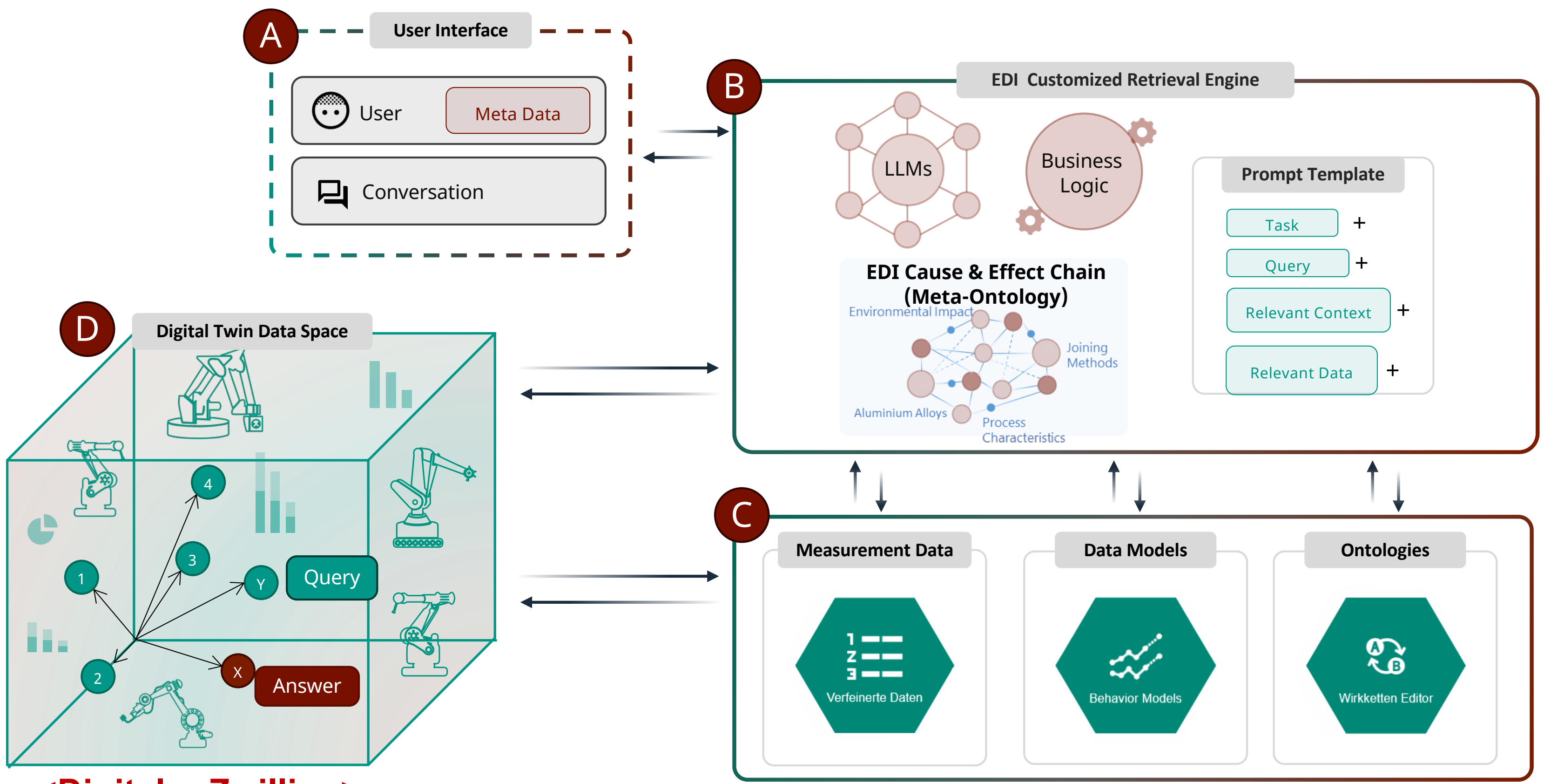
- **3. Workflow GUI for Non-programmers:**
  The graphical workflow (second slide) allows other researchers to run the entire RSW simulation without touching code.
- All steps—from geometry update to last Abaqus run—are visually linked and modular.

Automating Simulation Chains Using the Pyiron Workflow-GUI

➢ Pyiron Workflow (GUI)



LLM-based Knowledge Management System (RAG)



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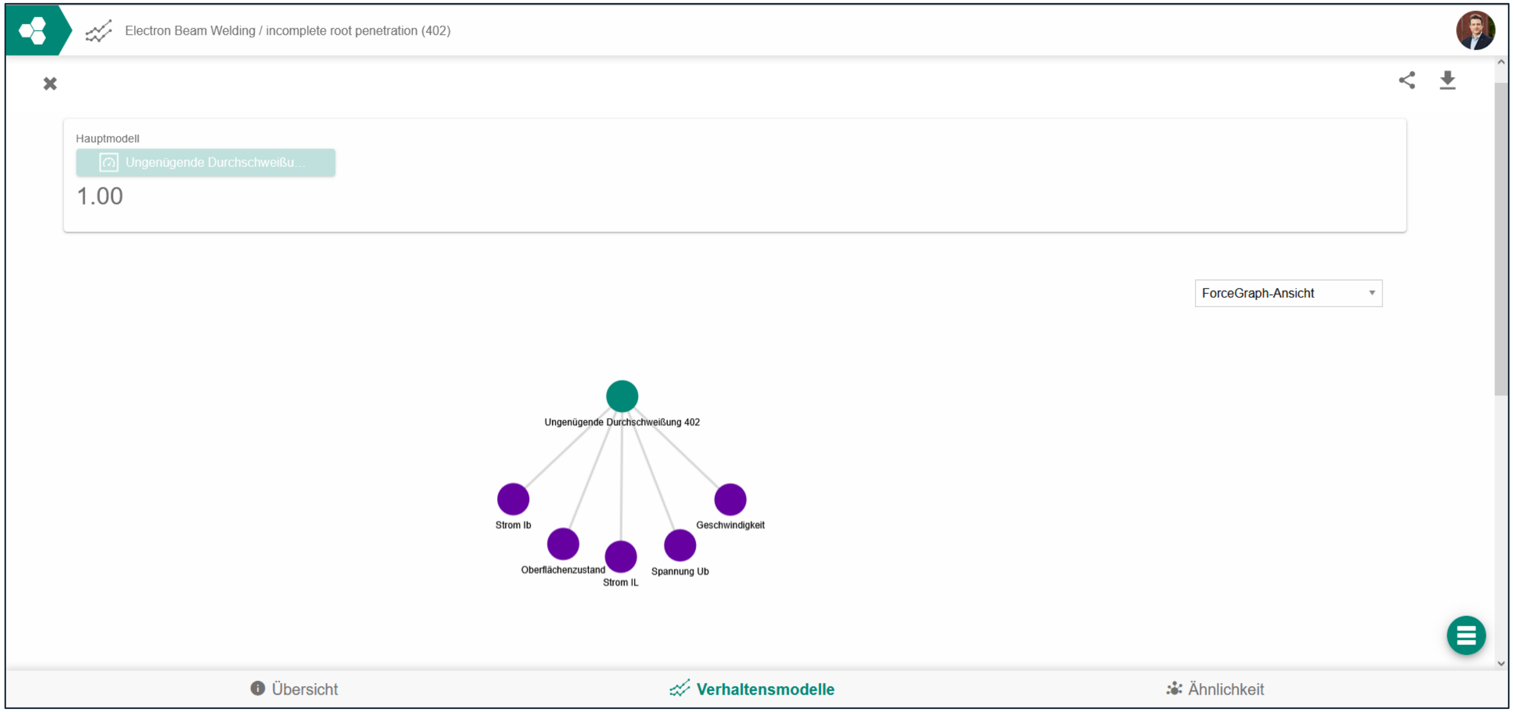
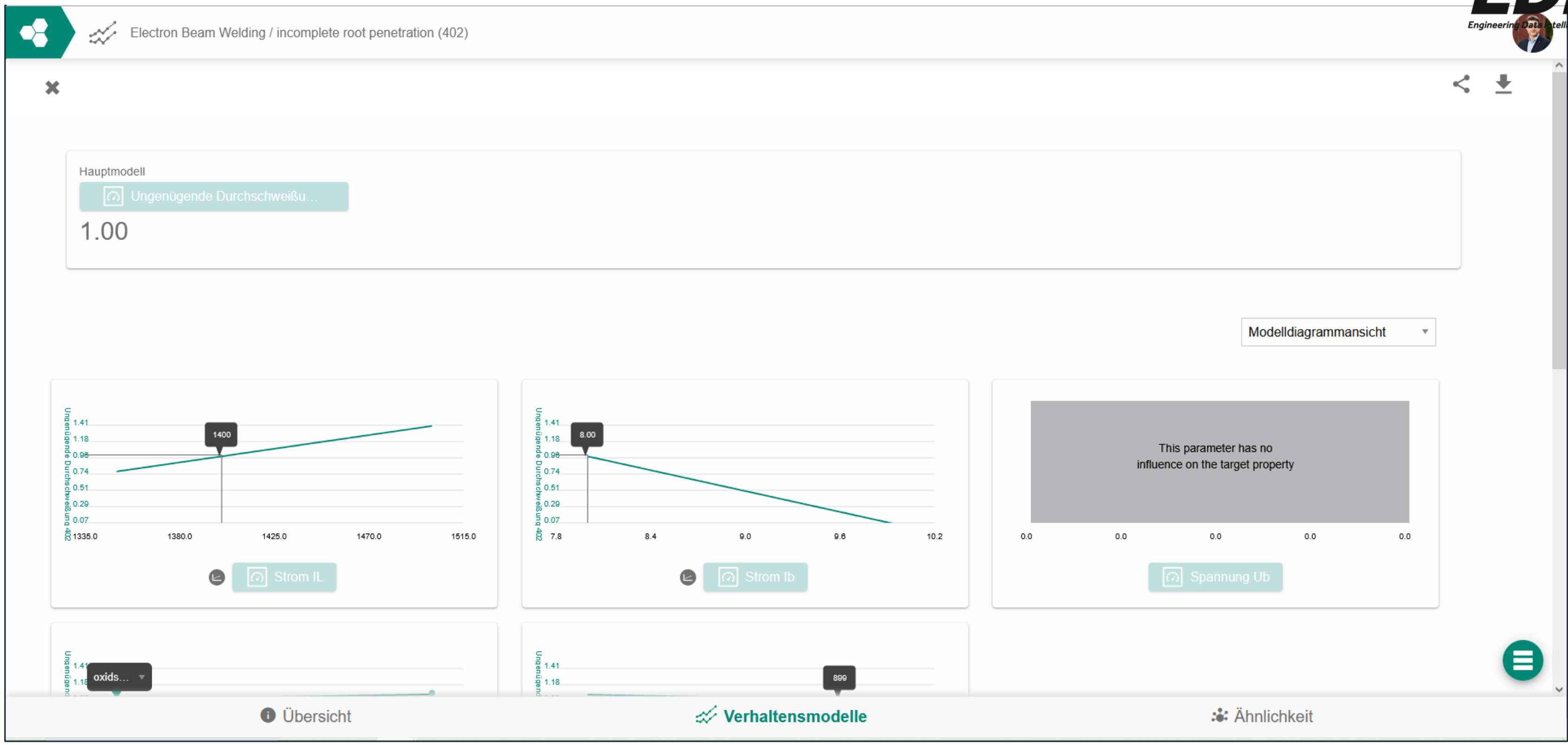
Backend: EDI hive IoT & KI Framework

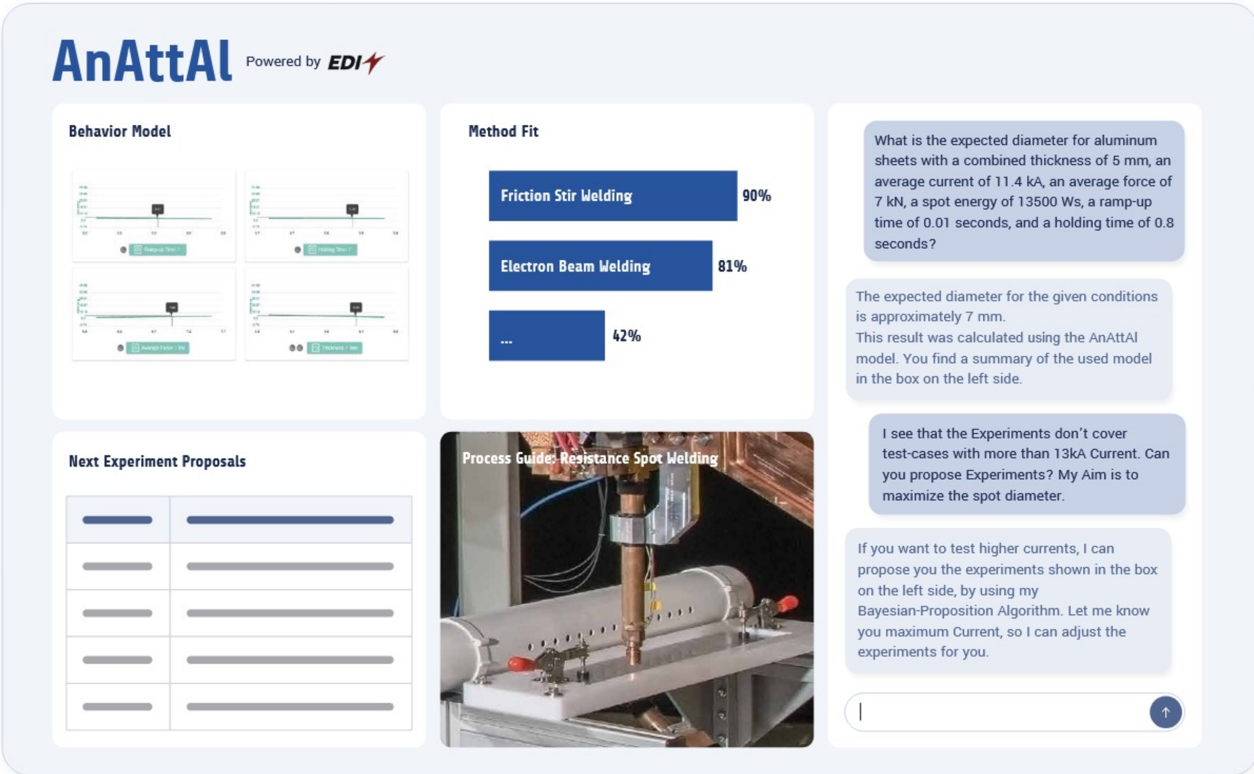
Datenbasis und KI-Hybridmodelle



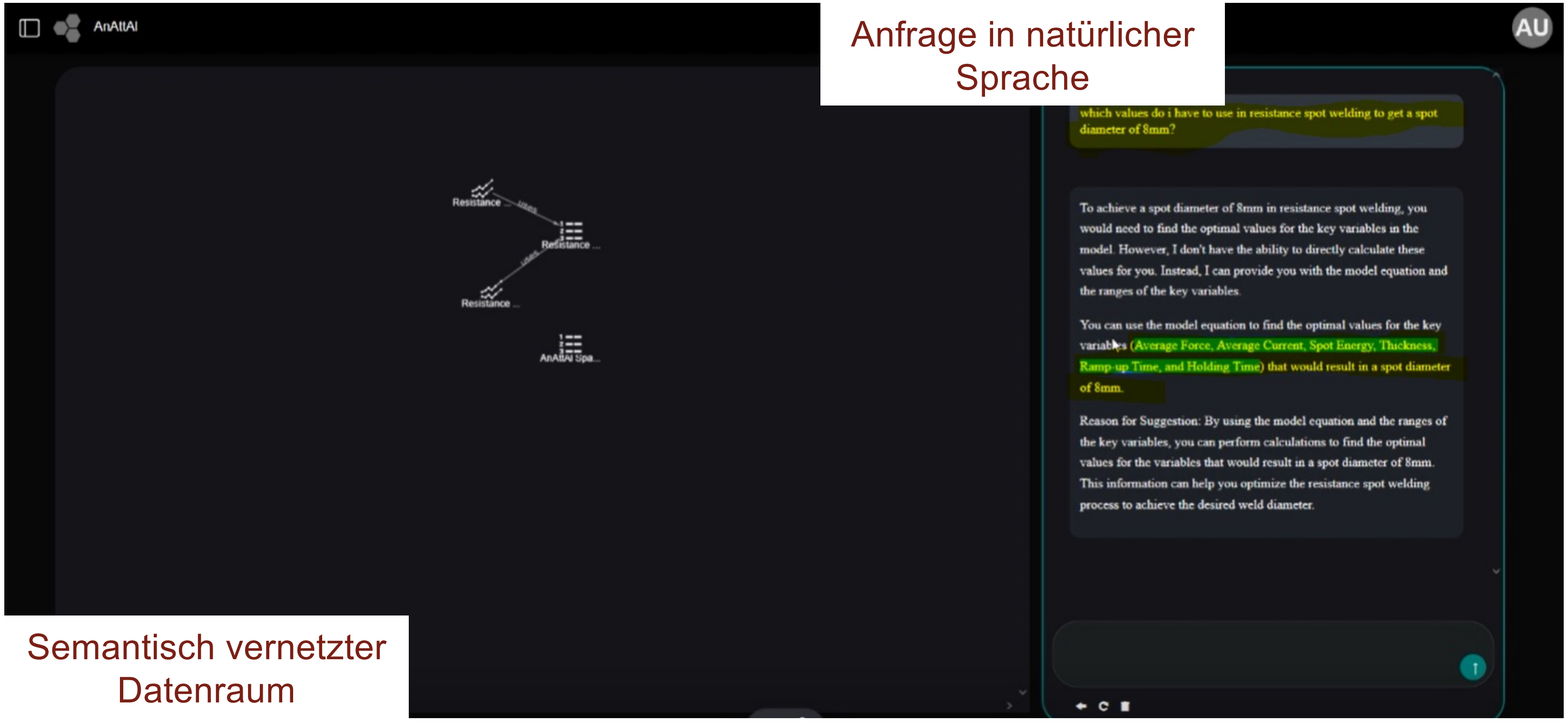
Datenbasis und KI-Hybridmodelle



Konzept: **KI-basierte Nutzung der Versuchsdaten**



Implementierung: KI-basierte Nutzung der Versuchsdaten



Anfrage in natürlicher Sprache

Semantisch vernetzter Datenraum

Outlook – Next Steps

- Validation of layer thickness measurements:
  - Cross-checking TEM results using complementary methods such as AFM, TOF-SIMS, and AES.

- Publication of results:
  - The findings from the different coating conditions and welding experiments will be published in the upcoming article [Working Title: Influence of Surface Conversion Coatings and Adhesive Layers on the Resistance Spot Welding of Aluminum Sheet Alloys EN AW-6016, EN AW-5182, and EN AW-6060].

- Contribution to PMD² AEM Special Issue:
  - Active participation and contribution to the PMD² special issue of Advanced Engineering Materials.
  - [Working Title: Integration of OpenCV-Based Microscopic Adhesive Volume Measurement into a Pyiron Workflow for Automated Data Analysis]

Thank You

Sung-Min Wi; Jiangdong Zhao; Andreas Fezer; Dr.-Ing. Martin Werz

Materials Testing Institute Stuttgart

Department Joining Technology and Additive Manufacturing

AnAttAl - Experimental and Simulative Analysis of Material- and Surface-Specific Attributes of High-Strength Aluminum Alloys

Back Up

Resistance Spot Welding at MPA

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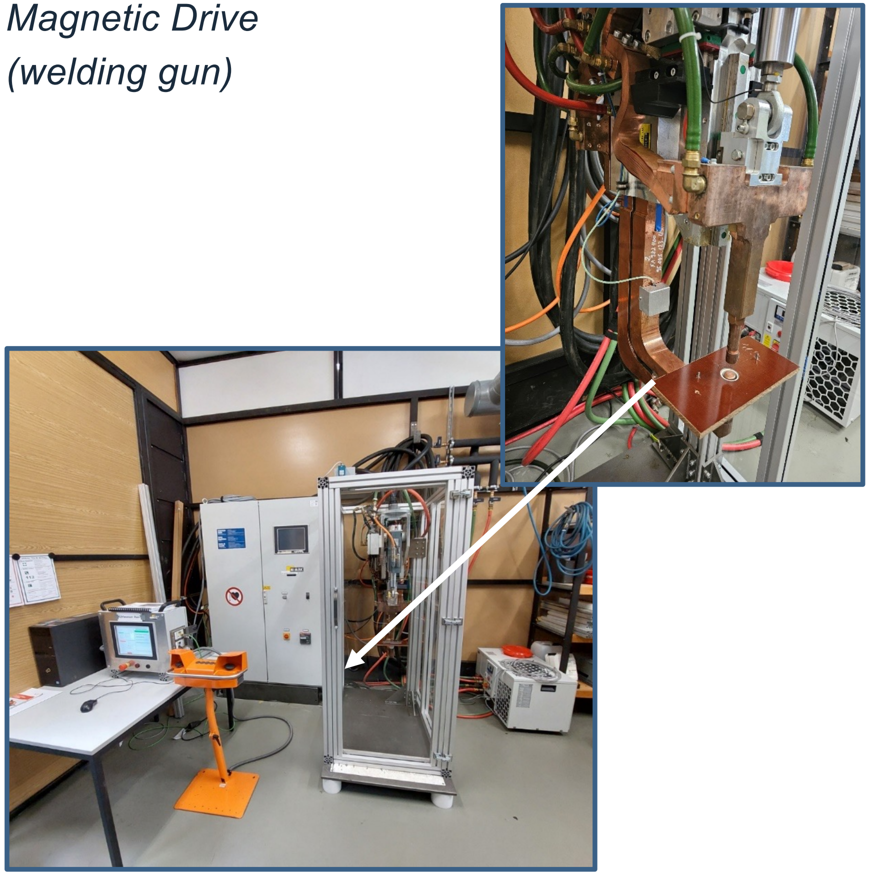
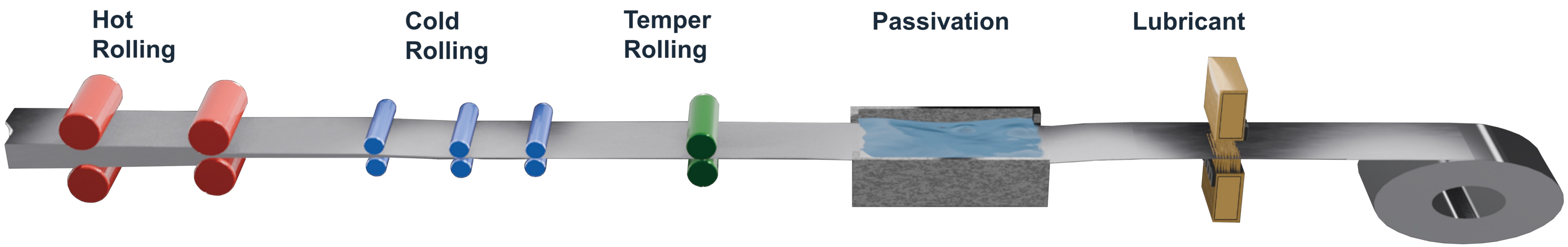
Magnetic Drive (welding gun)



OptiWAL Robot Cell

Aluminum sheet for the automotive industry

- Sheet metal production:

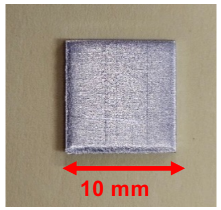


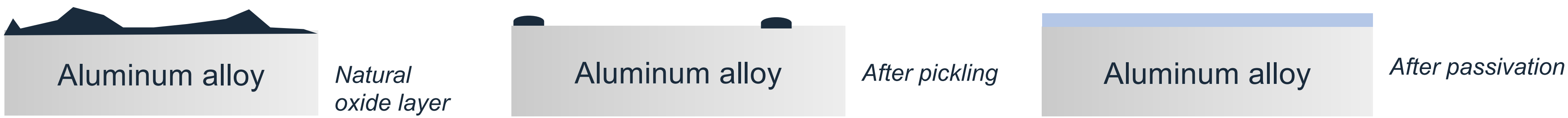
- <u>Passivation</u>:
  - Cleaning/Degreasing → Pickling → Passivation → Rinsing

Chemical

Strong alkaline solution
(NaOH or KOH concentrate)

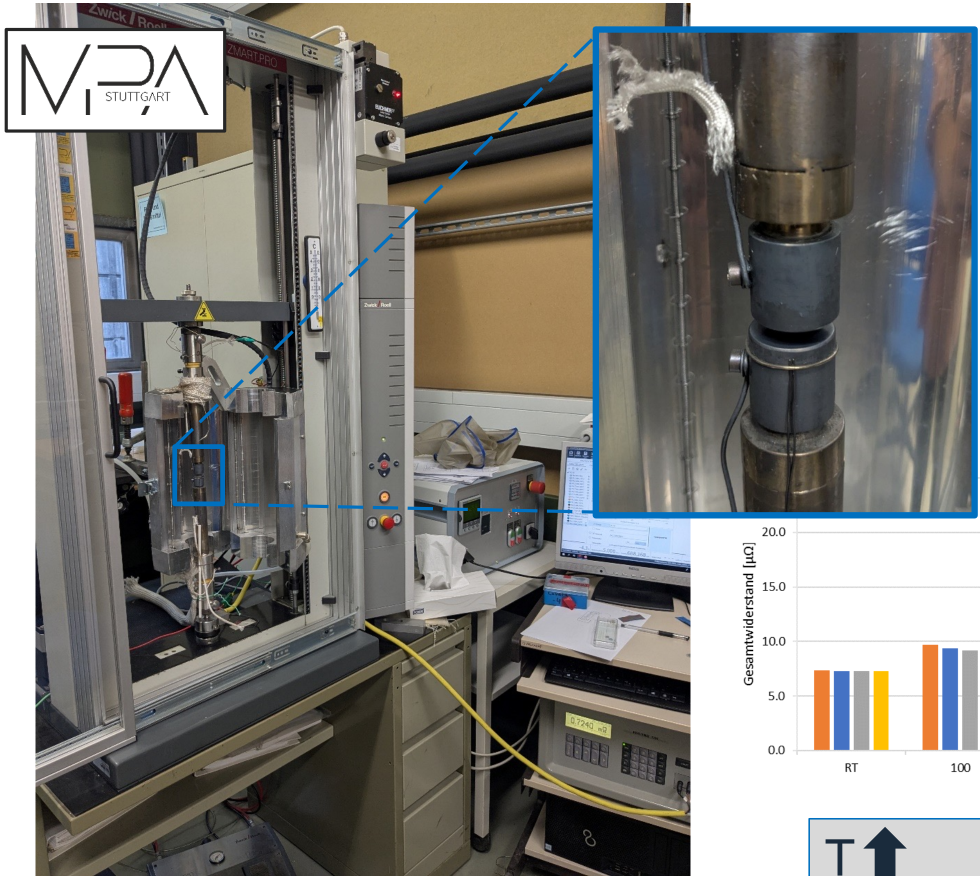
TiF + ZrF solution



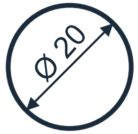


Schematic Illustration of Aluminum Alloy Passivation. Original diagram created by the author, conceptually based on information from Andreatta F et al. (2007)

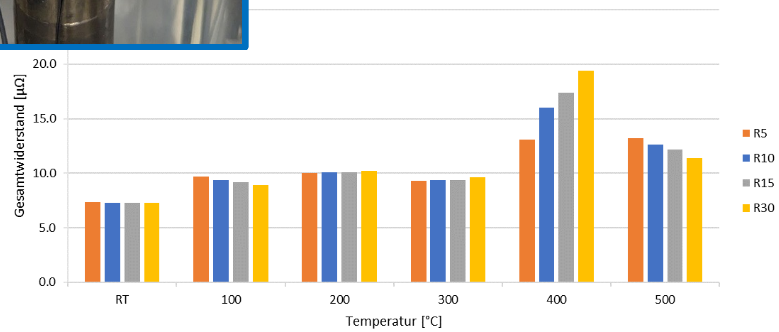
Contact Resistance at Elevated Temperatures

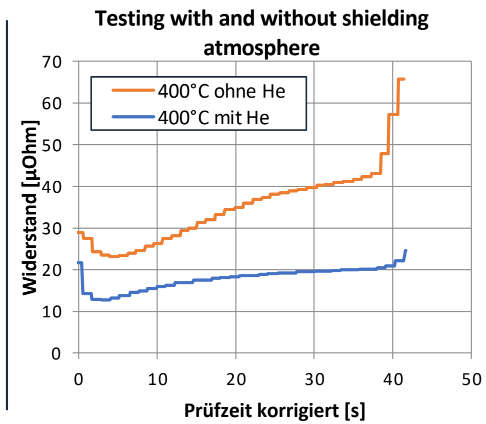


Specimen Geometry:



According to DVS Guideline 2929-1, I_{Mess} = 10 A , F = 7,5 kN

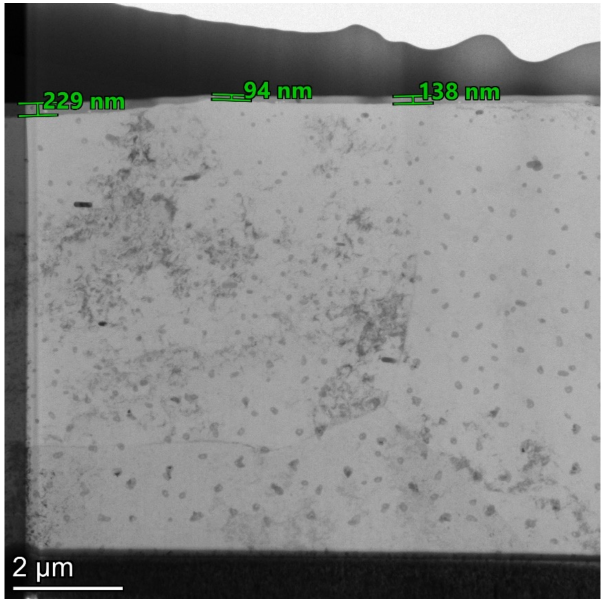




T ⬆ → Softening ⬆ + Oxidation ⬆

TEM – Special sample with 10 x more passivation

m_Ti ≈ m_Zr ≈ 45 mg/m² / AL6016

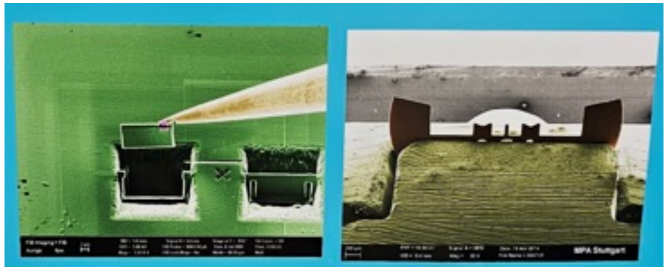


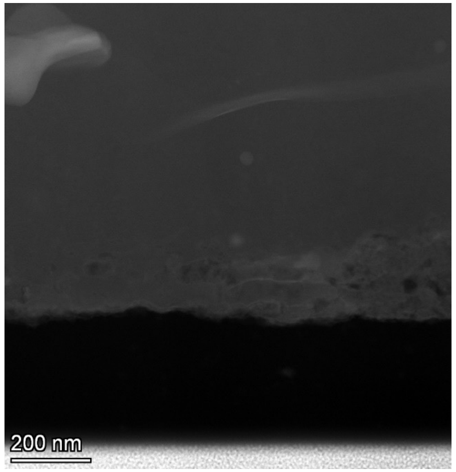
FIB-Schnitt – TEM

- Präparation für die TEM : Querschnitt durch FIB-Schnitt (100 x 100 nm)
  - Dünne Lamelle wird senkrecht zur Probenoberfläche herausgeschnitten.
- TEM-Aufnahme (*Florian Kauffmann* durch AMICA-Vorhaben)
  - Unregelmäßige Schichtdicke
    - Zwischen 25 nm bis 200 nm

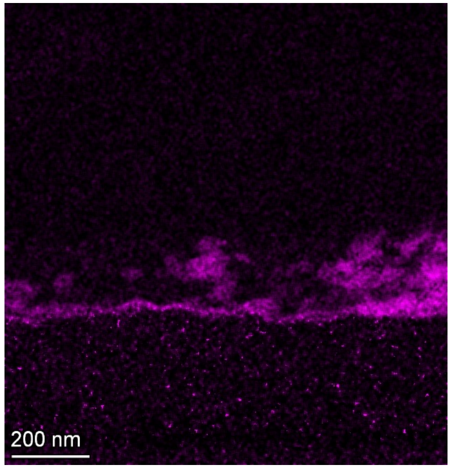
      Vermutung 1: Die Schicht ist inhomogen

      Vermutung 2: Durch die Oberflächenrauheit des Blechs ist die Projektion verschmiert.

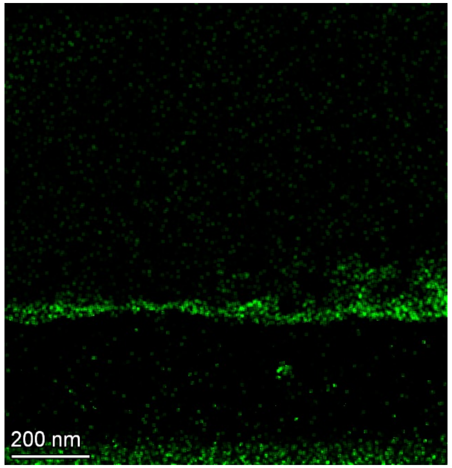

Ausschnitt vom Poster im UG (REM, TEM AMICA-Räume)



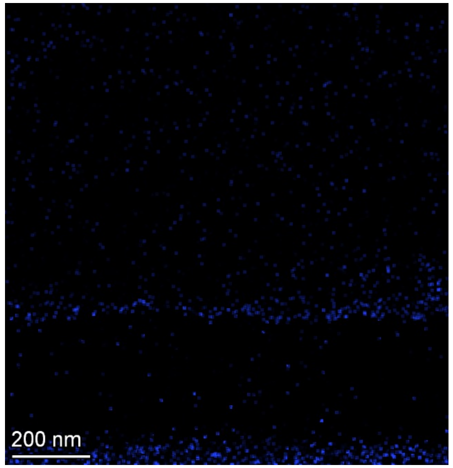
EN AW 5182 mit Ti/Zr Beschichtung



Mapping von O



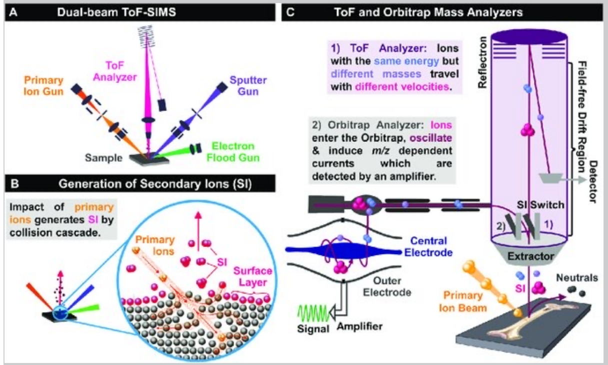
Mapping von Ti



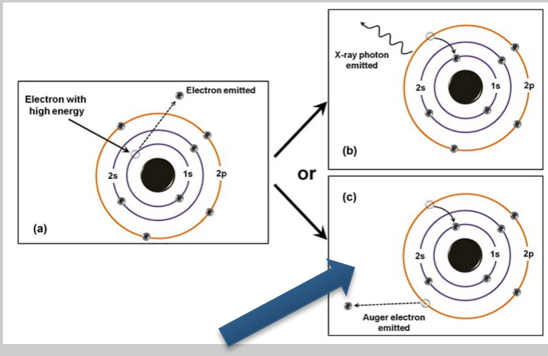
Mapping von Zr

Surface Analysis – possible methods

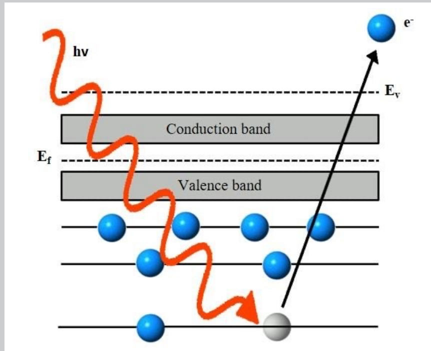
TOF-SIMS (Time-of-Flight Secondary Ion Mass Spectrometry)	AES (Auger Electron Spectroscopy)	XPS (X-ray Photoelectron Spectroscopy)
Incoming Particle: Ion Beam **Detected Signal:** Secondary Ions Using a primary ion beam, atoms and molecules are sputtered from the surface, releasing secondary ions. These secondary ions are analyzed using time-of-flight mass spectrometry.	**Incoming Particle:** Electron Beam **Detected Signal:** Auger Electrons An electron beam removes an electron from an inner shell of an atom. The resulting electron vacancy is filled by an electron from a higher shell. The excess energy is transferred to another electron, which is then ejected from the atom. The analysis of the kinetic energy of these element-specific Auger electrons allows determination of chemical composition.	**Incoming Particle:** X-ray photons **Detected Signal:** Photoelectrons Using X-ray photons, core electrons are ejected from atoms in the surface. The kinetic energy of these photoelectrons is measured, allowing determination of the elements present and their chemical bonding states. Angle-Resolved XPS → C-O contamination of sample



DOI: 10.1116/6.0002820



Surface Characterization of Biomaterials; Huaiyu Wang, Paul K. Chu, in *Characterization of Biomaterials (2013)*



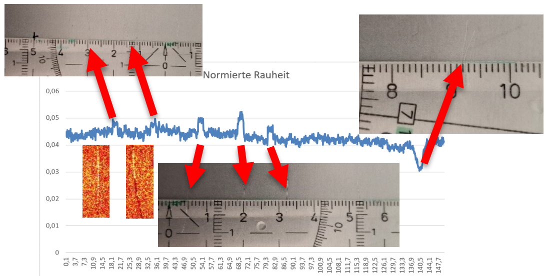
Hortigüela, María & Irurueta, Gonzalo. (2019). X-ray Photoelectron Spectroscopy A surface characterization technique.

Electron Beam Welding

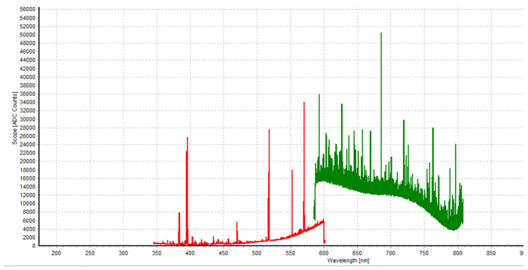
Project Results

- Laser Speckle: Identification and mapping of surface defects on the sheets
- Electron Beam Spectrometry: Determination of alloy composition during the welding process
- Welding Defects: Analysis of backscattered electrons

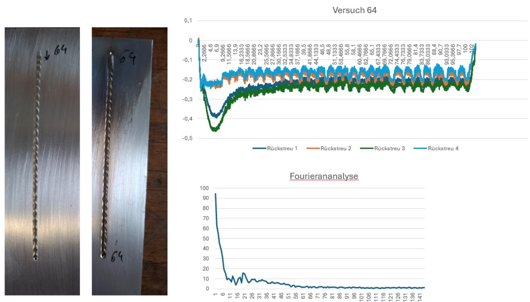
Laser Speckle



Elektronenstrahl-Spektrometrie



Rückstrahlelektronen



Charakterisierung - Zusammenfassung

Analyse	Topographie	Schmierstoff	Passivierung (Schichtdicke)	AnAttAI
TEM (mit FIB)			bedingt (20 – 200 nm)	Ja
3D Profilometer	Ja (Rauheit)			Unsicher
3D Lasermikroskop	Ja (Rauheit + Texturierung)			Ja
AFM	Ja (Rauheit, Bereich klein)	bedingt		Unsicher
RFA			bedingt (4 mg/m²); aber keine direkte Schichtdicke	Unsicher
FT-IR		Ja (0,8 mg/m²)		Ja
TOF-SIMS			Ja (Kalibrierung; 3,1 nm)	Ja, vielleicht
AES			Ja (Kalibrierung; 12 bis 15 nm)	Ja, vielleicht
LIBS			bedingt bis nein (keine Angabe)	Nein
XPS			Ja (0,6 nm)	Ja, vielleicht
ATR-IR		bedingt		Nein
Raman Spektroskopie			Nein, da Probe mit Rauheit	Nein
Ellipsometrie		nein	Ja aber Modellierung notwendig; dafür in Raumbedingung möglich.	Unsicher
XRR		nein	Nein, da Probe zu rau.	Nein