Wire-based Additive Manufacturing of Magnesium Alloys

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TOMORROW TODAY

Interreg project „ReMaP“, ATCZ229

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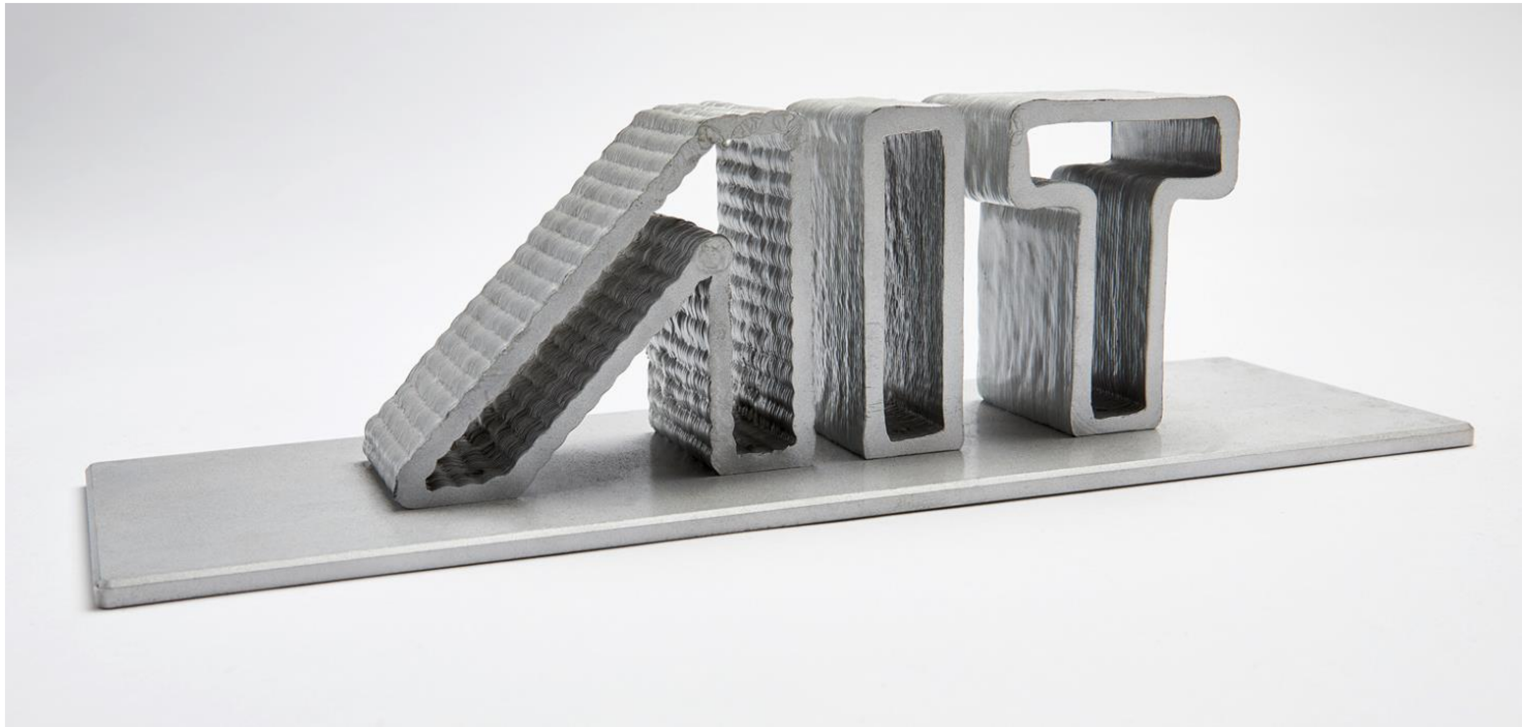
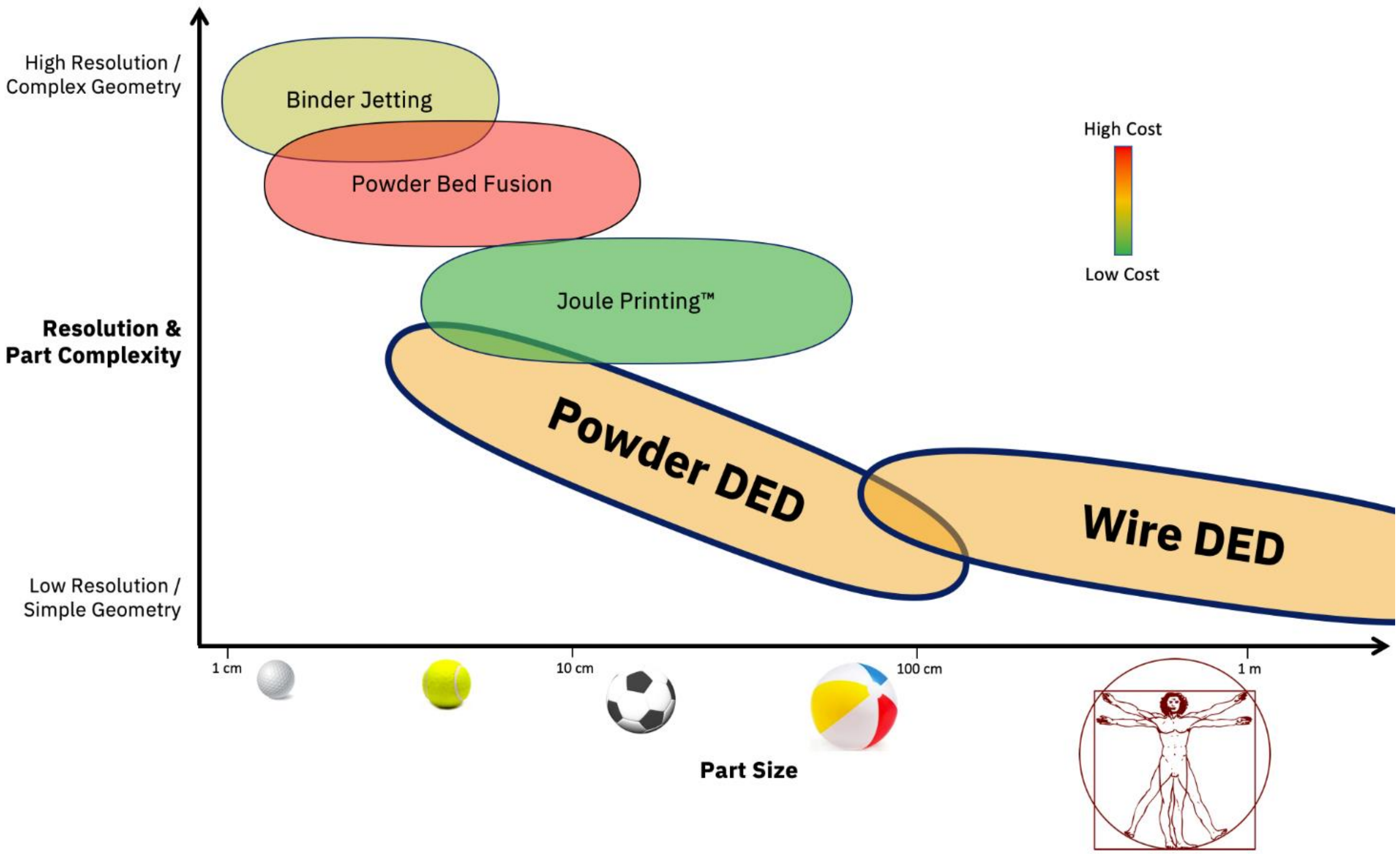
CONTENTS

- Additive manufacturing of Mg – overview
- Wire additive manufacturing (WAM)
- Projects at LKR



COMPARISON OF METAL AM TECHNOLOGIES



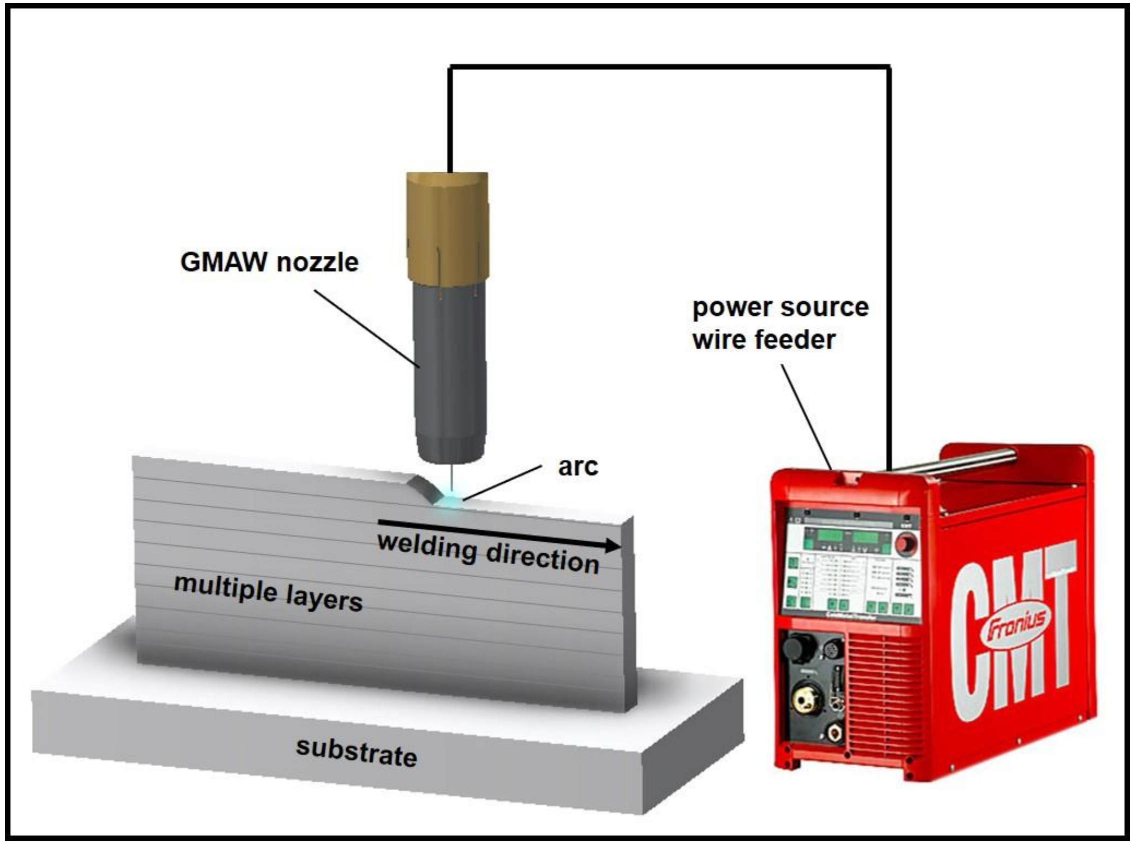
[1] DigitalAlloys, Digital Alloys‘ Guide to Metal Additive Manufacturing – Part 9: Directed Energy Deposition (DED) (2019). https://www.digitalalloys.com/blog/directed-energy-deposition/

WIRE-BASED ADDITIVE MANUFACTURING

+ Standard welding equipment
+ High deposition rates with nearly unlimited space (compared to powder-based processes)
+ Material efficient (compared to subtractive methods)
+ Short lead times

Usable materials: Titanium, steel, nickel, aluminum and magnesium alloys

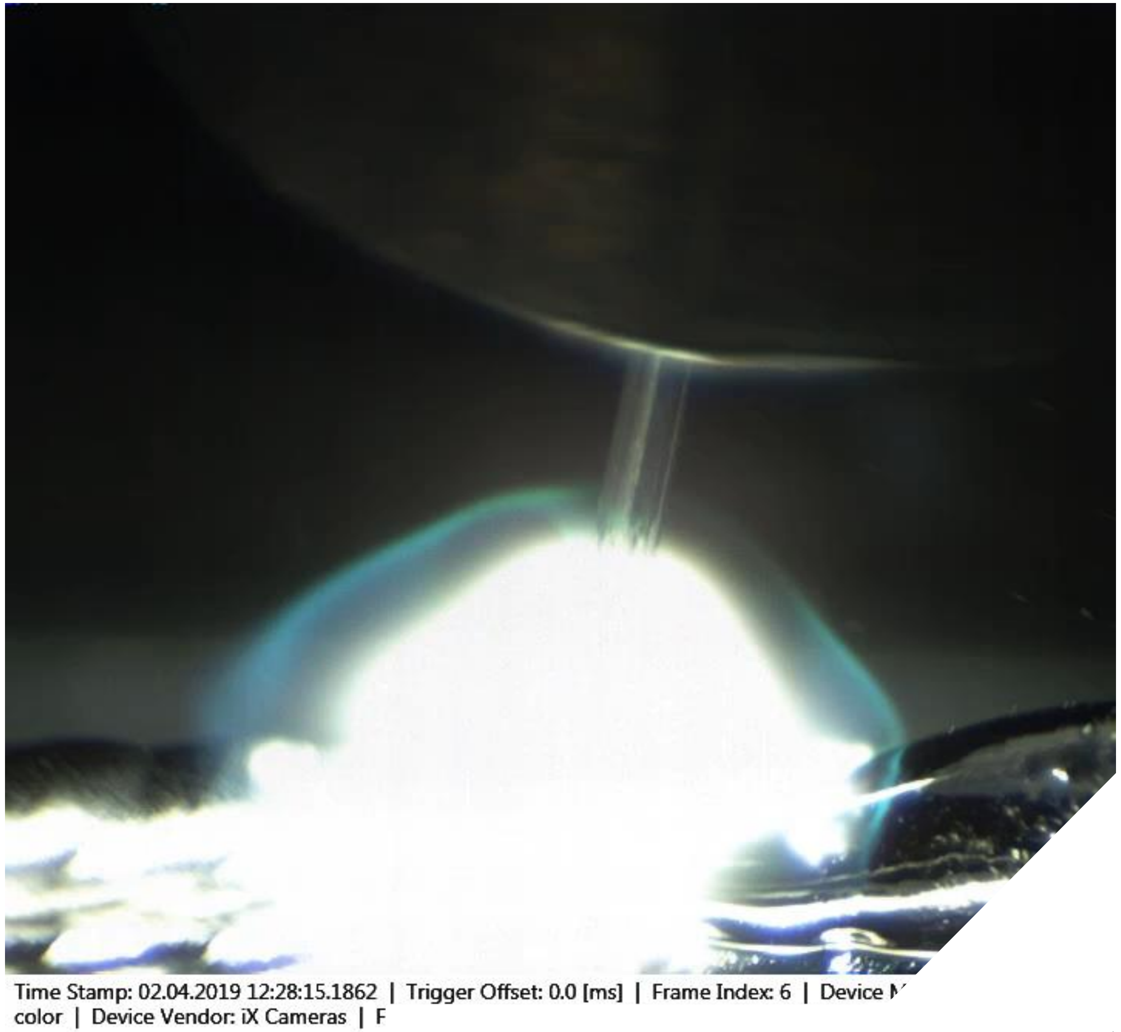
- Limited part complexity
- Limited ability to produce thin walls
- Post-processing (machining) necessary



Schematic representation of the WAAM process

WIRE-BASED ADDITIVE MANUFACTURING

- Building space limited by handling device only
- Possible deposition rates
  - Titanium 3.7 kg/h [2]
  - Aluminum 2 kg/h
  - Steels 4 kg/h [2]
  - **Magnesium 1 kg/h**
- Layer dimension/precision ≈ 3 mm
- Automatic CAD/CAM interface in prototyping phase



[2] R. Grunwald, M. Mayer, M. Schörghuber, WAAM – Technologie und aktuelle Anwendung, in: DVS-Berichte Band 344, 97.

WIRE-ARC ADDITIVE MANUFACTURING AT AIT/LKR

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Power sources

- CMT Advanced, CMT-TWIN (Fronius)
- Magic WAVE 5000 (Fronius)
- PlasmaMultiInverter 350 AC/DC TL (SBI)

ABB robot system

- Robot with 45 kg max. load
- Workpiece positioner

KUKA robot system

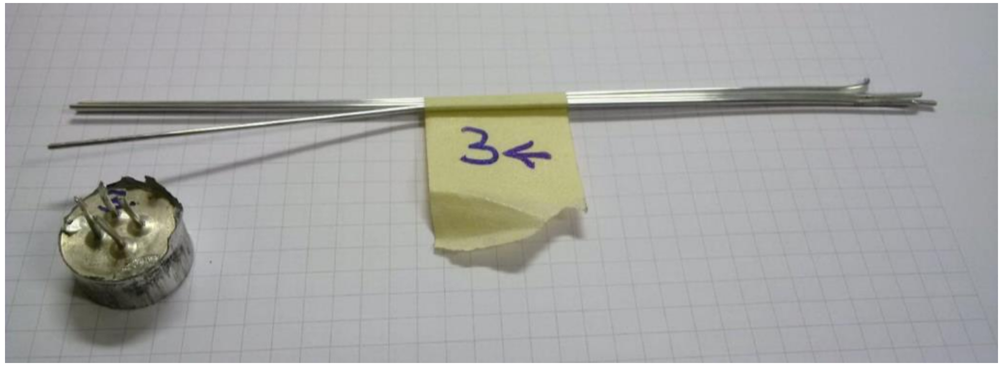
- Robot with 300 kg max. load
- Workpiece positioner

→ **Basic equipment for light metal WAAM**

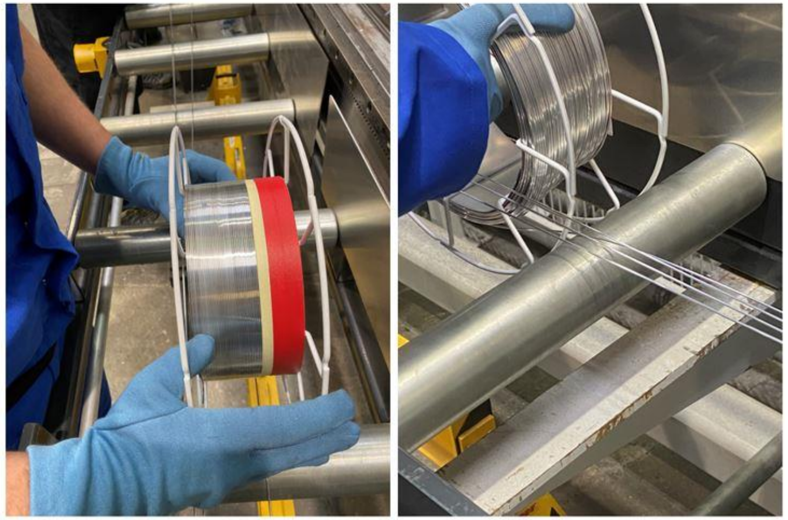
FILLER WIRE MANUFACTURING VIA EXTRUSION

Extrusion pressing of Mg alloy wires

- Small scale wire manufacturing plant
- Special wires and custom alloys for R&D
- Diameters 0.8 – 6 mm
- 0 – 30 kg batch size
- Larger batch sizes with industrial collaboration

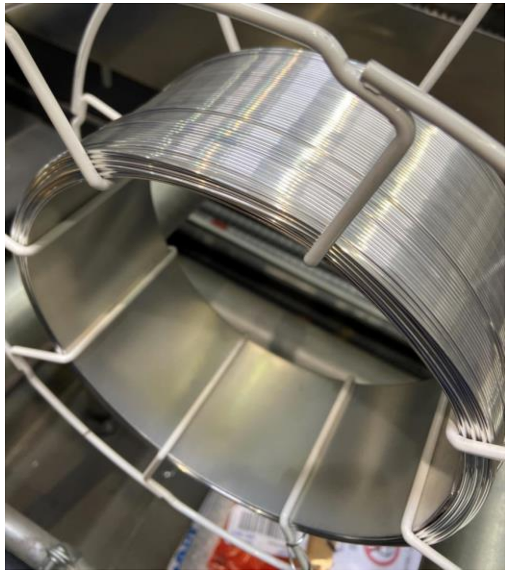


Wire sections and residue



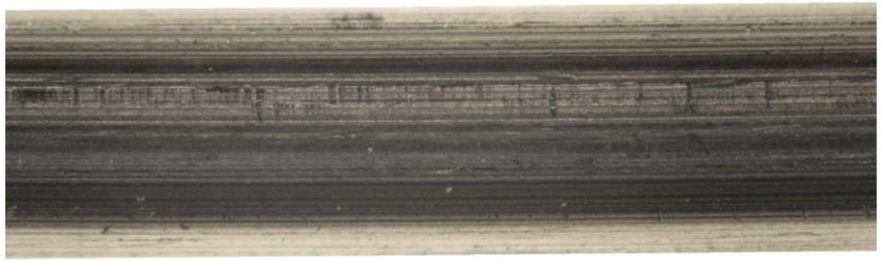
Coil at extrusion press roller table

Interreg Austria-Czech Republic



Single wire coil

Pressed wire Ø 1.2 mm

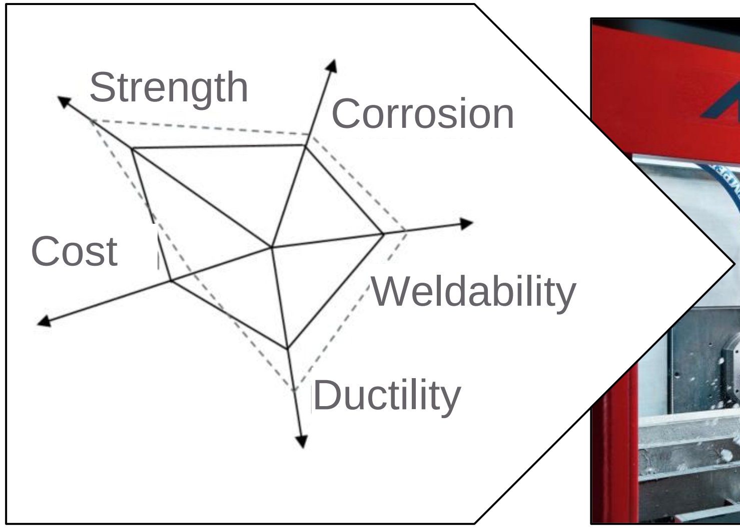


Drawn wire Ø 1.6 mm

Surface quality of extruded (pressed) wire vs. commercial (drawn) wire

1 mm

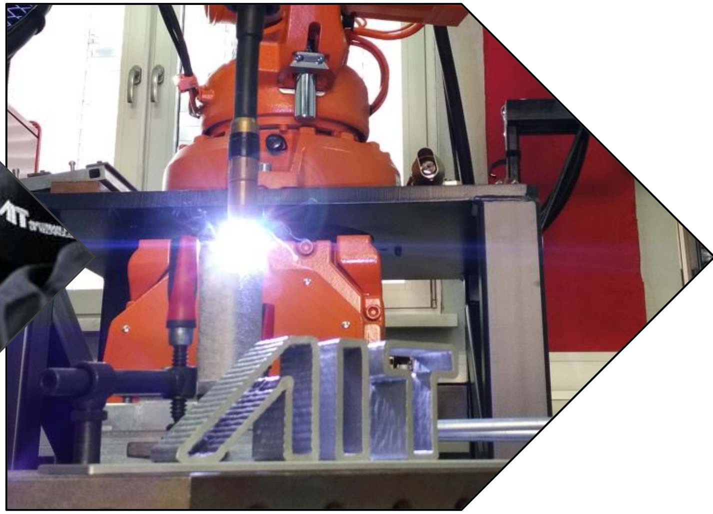
WAAM-SPECIFIC ALLOY DEVELOPMENT



Alloy design

Casting

Wire production

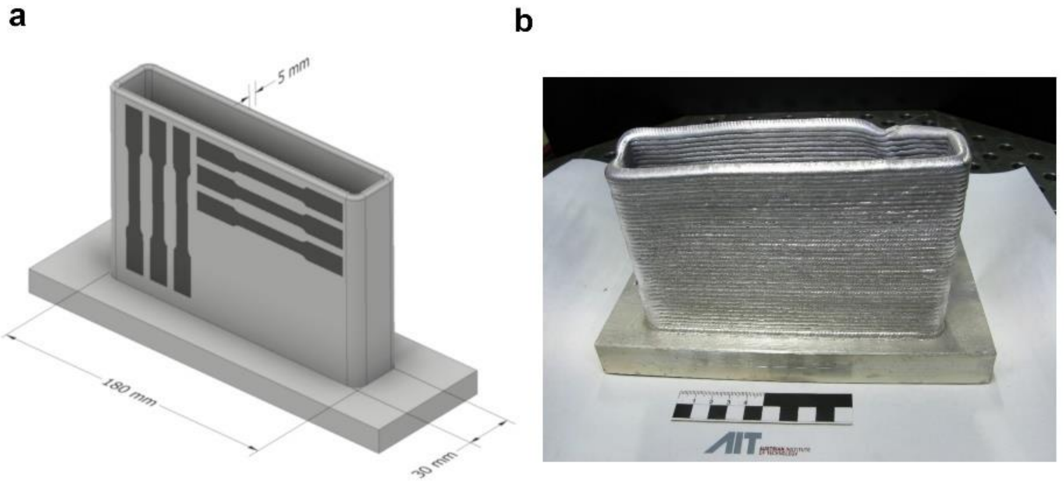


Welding and characterization

Cost efficient wire production route for special wire compositions from concept to prototype

STARTING POINT: WAAM OF MG-AZ61

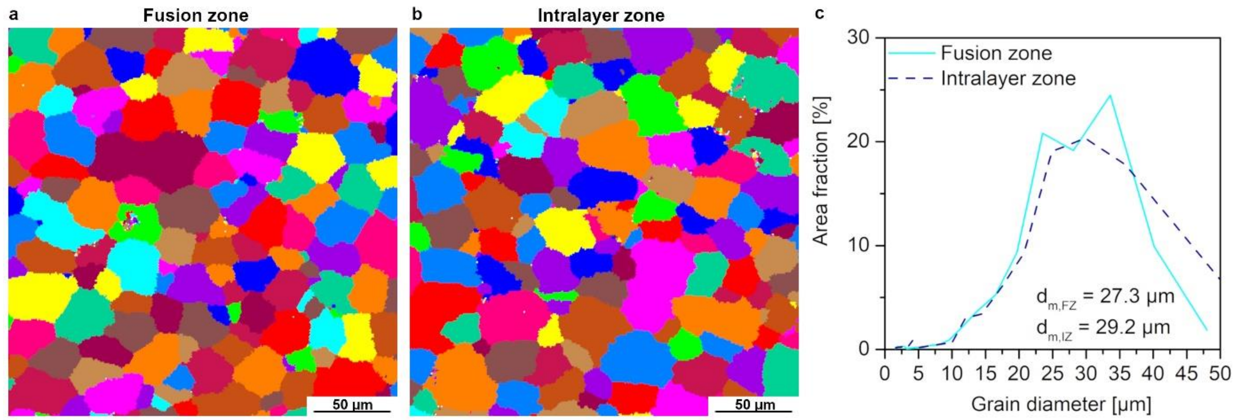
- Commercial available AZ61 filler wire
- Cold metal transfer (CMT) process
- Sample size 180 x 30 x 80 mm
- Wall thickness 5 mm
- Surface roughness ~ 0.3 mm
- DR: 0.39 kg/h @ 1.6 mm wire



Details of the specimens fabricated for subsequent characterization. (a) Scheme inclusive tensile specimen locations; (b) photograph of the Mg AZ61A sample fabricated by WAAM

Yield strength (L/T)	Tensile strength (L/T)	Fracture strain (L/T)
MPa	MPa	%
99.2 ± 1.7 / 104.4 ± 1.6	256.4 ± 10.1 / 264.1 ± 1.8	15.3 ± 3.5 / 15.4 ± 0.7

Mechanical properties (tensile, room temperature)
L = Longitudinal (welding direction)
T = Transversal (perpendicular to welding direction)



Grain structures (a,b) and grain size distribution (c)

	Mg [wt. %]	Al [wt. %]	Zn [wt. %]	Mn [wt. %]
Wire	92.3	6.7	0.63	0.33
WAM deposit	92.8	6.3	0.62	0.34

Chemical compositions of the wire and the additively manufactured part

T. Klein, A. Arnoldt, M. Schnall, S. Gneiger: Microstructure Formation and Mechanical Properties of a Wire-Arc Additive Manufactured Magnesium Alloy, JOM, The Minerals, Metals & Materials Society, 2021

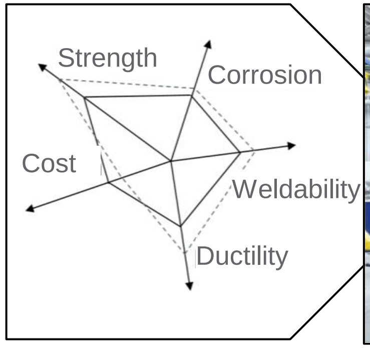
ALLOY AND PROCESS DEVELOPMENT FOR WAAM AND LPBF

- Research on magnesium alloys for additive manufacturing of structural and biodegradable components “ReMaP”. (2020-2022)

AIT/LKR: Material selection + alloy development, wire manufacturing, WAAM processing

Technical University Brno: Powder production (wire atomization), LPBF processing

University of Applied Sciences Upper Austria: Characterization

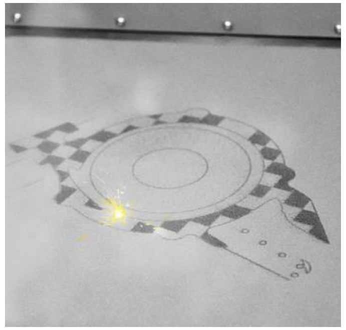


Alloy design

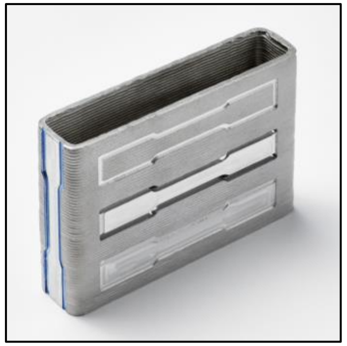
Casting

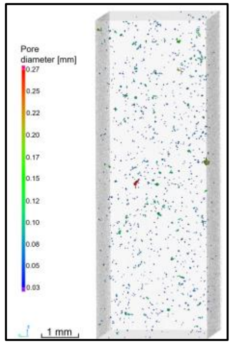
Wire production

Wire-arc additive manufacturing



Powder atomization and laser powder bed fusion





Characterization

ALLOY FOR STRUCTURAL COMPONENTS

AX13 (Mg-Al-Zn-Ca)

ALLOY DESIGN

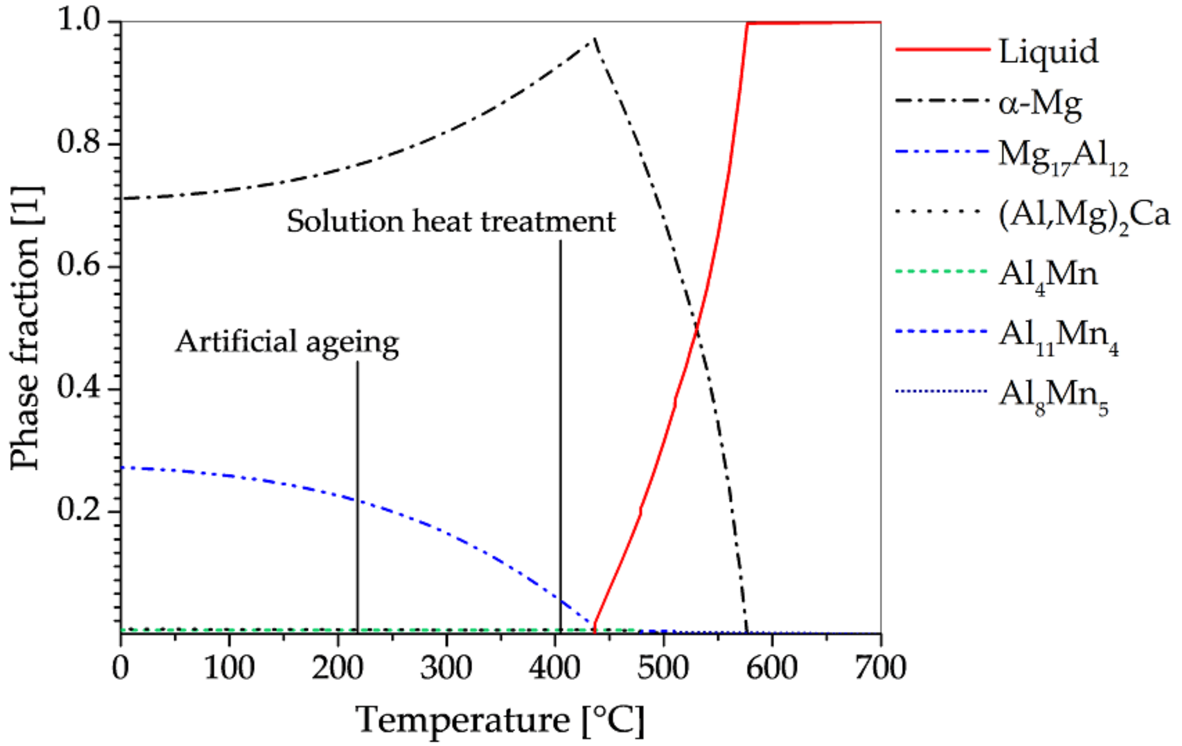
Alloy with high yield strength

- No rare earth elements
- Ca for oxidation resistance

Nominal chemical composition of alloy AX13

Alloy	Al [wt. %]	Zn [wt. %]	Ca [wt. %]	Mn [wt. %]	Mg [wt. %]
AX13	12.0 – 15.0	0.30 – 0.60	0.30 – 0.50	0.15 – 0.50	Rem.

Equilibrium thermodynamic calculation of alloy AX13



Substantial amounts of β-phase ($Mg_{17}Al_{12}$)

Increase of mechanical properties by artificial ageing

AX13 SAMPLE PREPARATION

Wire-based additive manufacturing of specimen using the gas-metal arc-welding cold metal transfer (CMT) process

- weld speed 12 mm/s
- wire feed rate 2.0 m/min (base layer) and 1.5 m/min (building layers)
- layer thickness ~ 2.5 mm
- wall thickness of 5 mm
- protective gas: Ar + 30 % He

- Tensile test samples and metallographic samples in welding- and transverse direction

Finished WAAM part out of alloy AX13

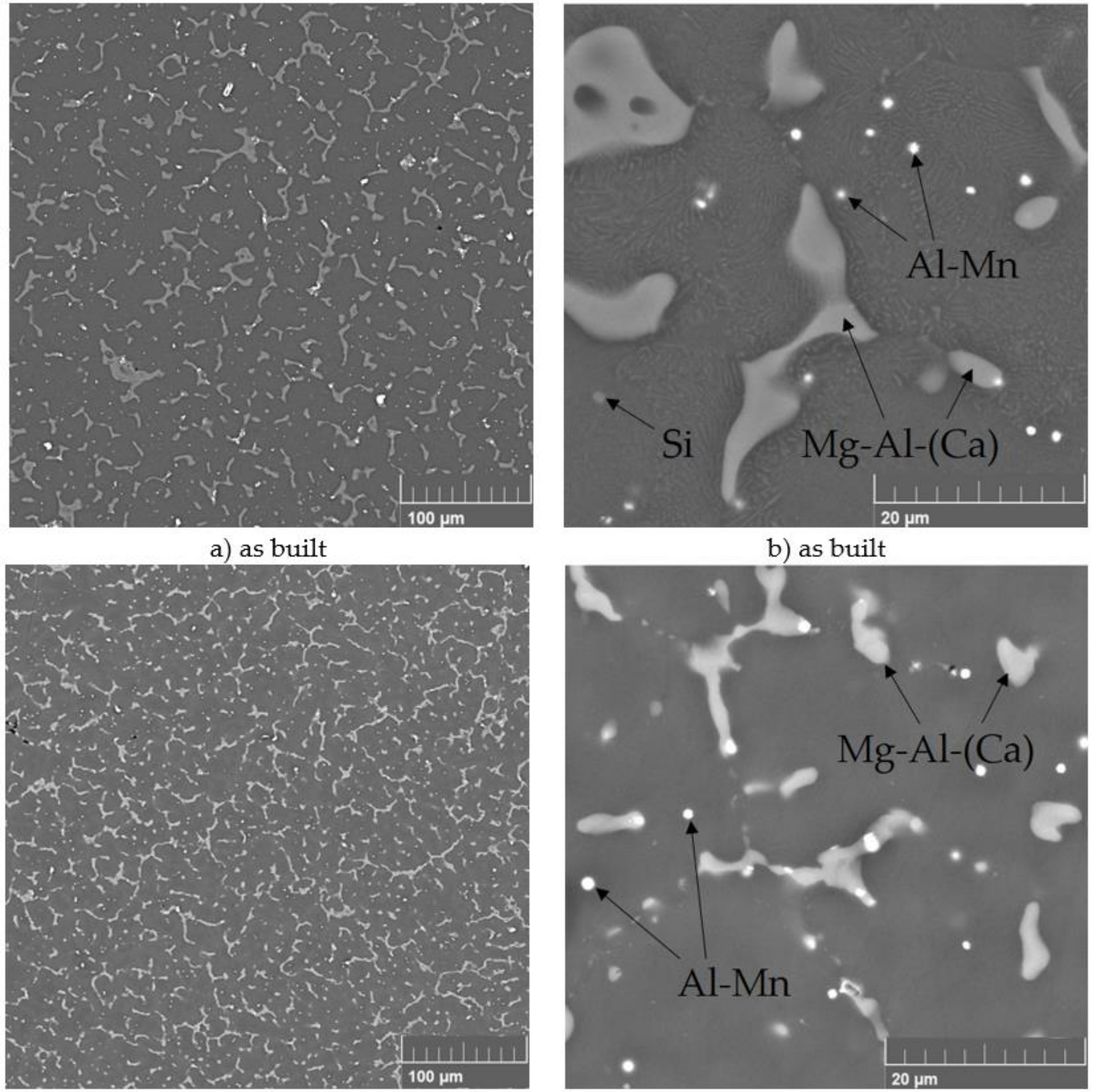
AX13 MICROSTRUCTURE

As built

- Network-like structure of divorced eutectic on the grain boundaries
- Al-Mn-phases
- Ca dissolved in the eutectic
- Lamallar eutectic structures inside the grains

After heat treatment

- Lamellar eutectic structures dissolved
- Divorced eutectic on the grain boundaries still present



a) as built b) as built c) T6 temper d) T6 temper

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AX13 MECHANICAL PROPERTIES

	YS [MPa]	UTS [MPa]	ε_f [%]
AX13 as built	157.4 ± 2.5	209.6 ± 9.7	0.9 ± 0.2
AX13 T6	190.9 ± 1.4	269.2 ± 10.6	1.4 ± 0.4

- In the as built state yield strength higher than that of AZ61 (+ 50%)
- Heat treatment leads to significant increase in YS and UTS (+21 % YS, +28% UTS)
- Overall low elongation at break
- Mechanical properties in welding direction and transverse direction almost identical

→ Adjustment of heat treatment parameters necessary to increase the amount of dissolved β-phase and thus exploit the full potential of the high Al content.

ALLOY FOR BIODEGRADABLE COMPONENTS

ZX10 (Mg-Zn-Ca)

ALLOY DESIGN / PROPERTIES

Alloy with high ductility

- Only elements suitable for medical applications
- Low corrosion potential
- Alloy ZX10 based on the work of Hofstetter et al. [3]

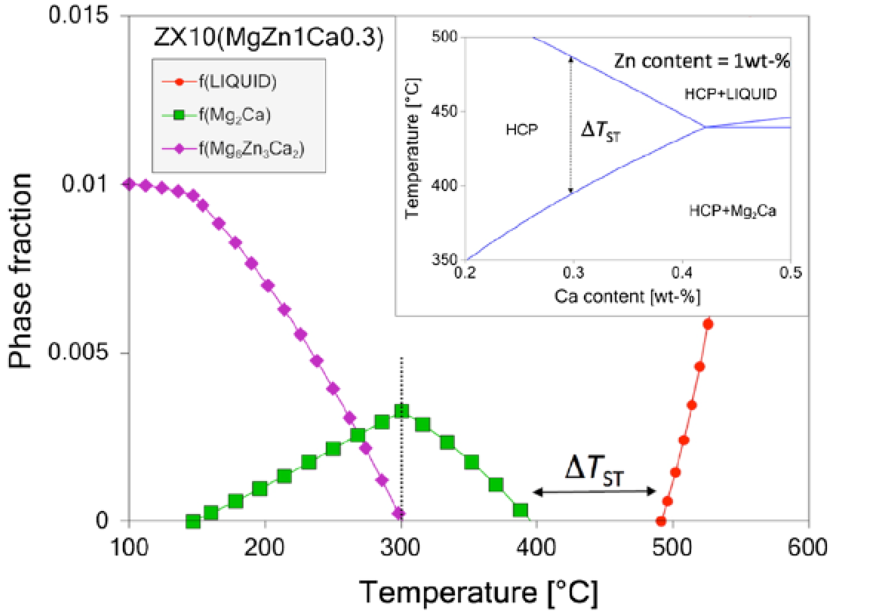
Mechanical properties of WAAM lower compared to extruded alloy [3]

→ Fine grain size achieved via extrusion (2 µm) not achievable via WAAM

	YS [MPa]	UTS [MPa]	ε_f [%]
ZX10 WAAM transverse dir.	75.8	210.9	20.5
ZX10 WAAM welding dir.	76.0	214.6	21.5
ZX10 extruded [3]	240	255	27

Mechanical properties (tensile) of alloy ZX10 [3]

Equilibrium thermodynamic calculation of alloy ZX10 [3]



[3] Hofstetter, J., Becker, M., Martinelli, E. *et al.* High-Strength Low-Alloy (HSLA) Mg–Zn–Ca Alloys with Excellent Biodegradation Performance. *JOM* **66,** 566–572 (2014). https://doi.org/10.1007/s11837-014-0875-5

SUMMARY AND OUTLOOK

Summary

- WAAM is a novel and advanced manufacturing process capable of fabricating large structures with reasonable deposition rates
- WAAM-specific material development is required for further exploitation
- The complete manufacturing chain from casting to wire fabrication and WAAM is conducted at LKR

Outlook

- Future projects will focus on the optimization of alloy concepts for WAAM processes
- WAAM processes will be aided by simulation and path planning tools
- Process optimization using various sensing and data analysis concepts

ACKNOWLEDGEMENTS

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THANK YOU!

Stefan Gneiger, 02.03.2022

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