ADDITIVE MANUFACTURING OF STRUCTURED COMPONENTS FROM MAGNESIUM ALLOY

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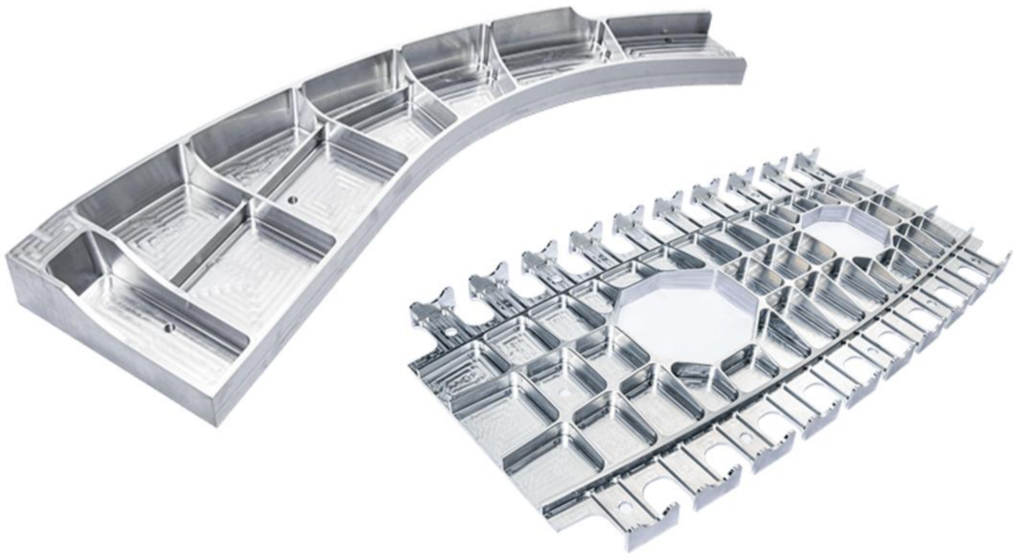
AND **INDUSTRIAL DESIGN**

CONTENT

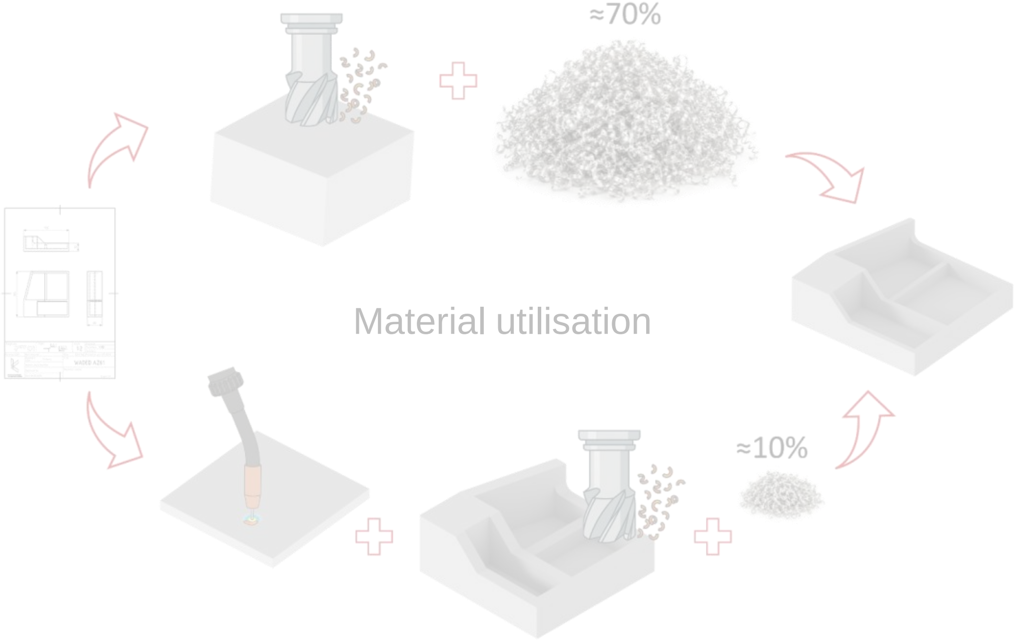
Introduction and Motivation

Material utilisation efficiency

- Conventional production of large aircraft components - subtractive manufacturing (milling from large blanks)
- Material utilisation efficiency is described by the Buy-to-Fly (BTF) ratio (commonly 10:1)
- Additive Manufacturing (AM) – material deposited only where functionally required
- WADED could be a highly promising technology for these components



Aircraft a) C-shape frame, b) wing rib (visionwide-tech.com)



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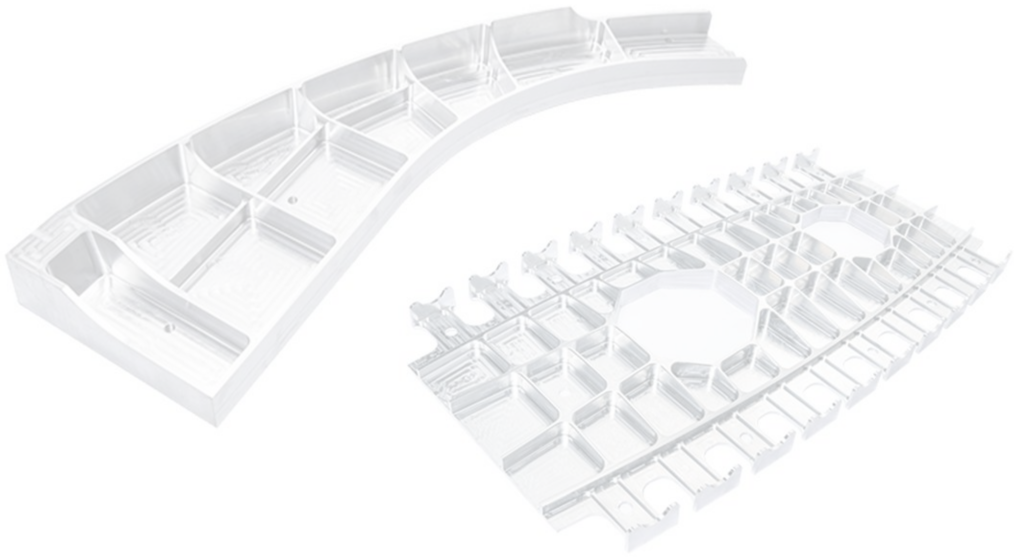

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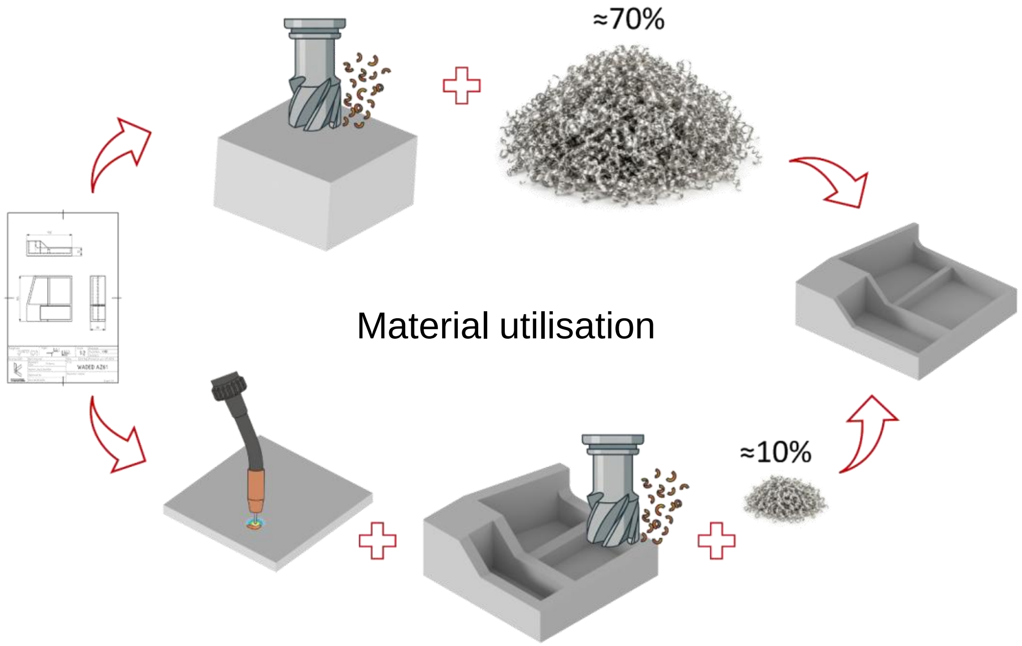

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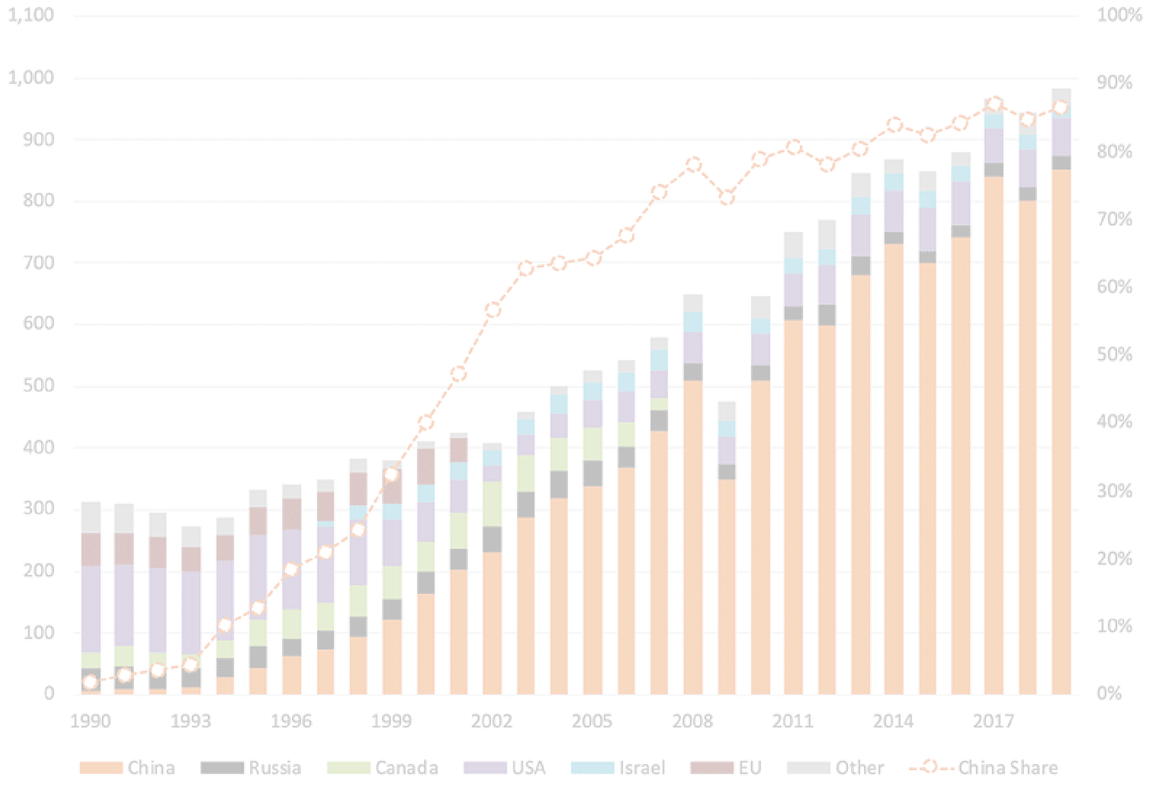
Introduction and Motivation

Magnesium alloys

- The low density and high strength-to-weight ratio
- Sustainability: Replacing materials with Mg alloys could significantly reduce the environmental impact of transportation
- Most promising green engineering material in the 21st century

Alloy (wrought)	Al6061 – T6	AZ61 – as fabricated
Density ($kg \cdot m^{-3}$)	2700	1800
Tensile strength - Ultimate (MPa)	310	310
Tensile strength - Yield (MPa)	275	230
Elongation (%)	12	11
Specific yield strength ($kN \cdot m \cdot kg^{-1}$)	**102**	**128**

ASM Specialty Handbook (Davis, Avedesian)



Global primary magnesium production by country - kt (energyindustryreview.com)

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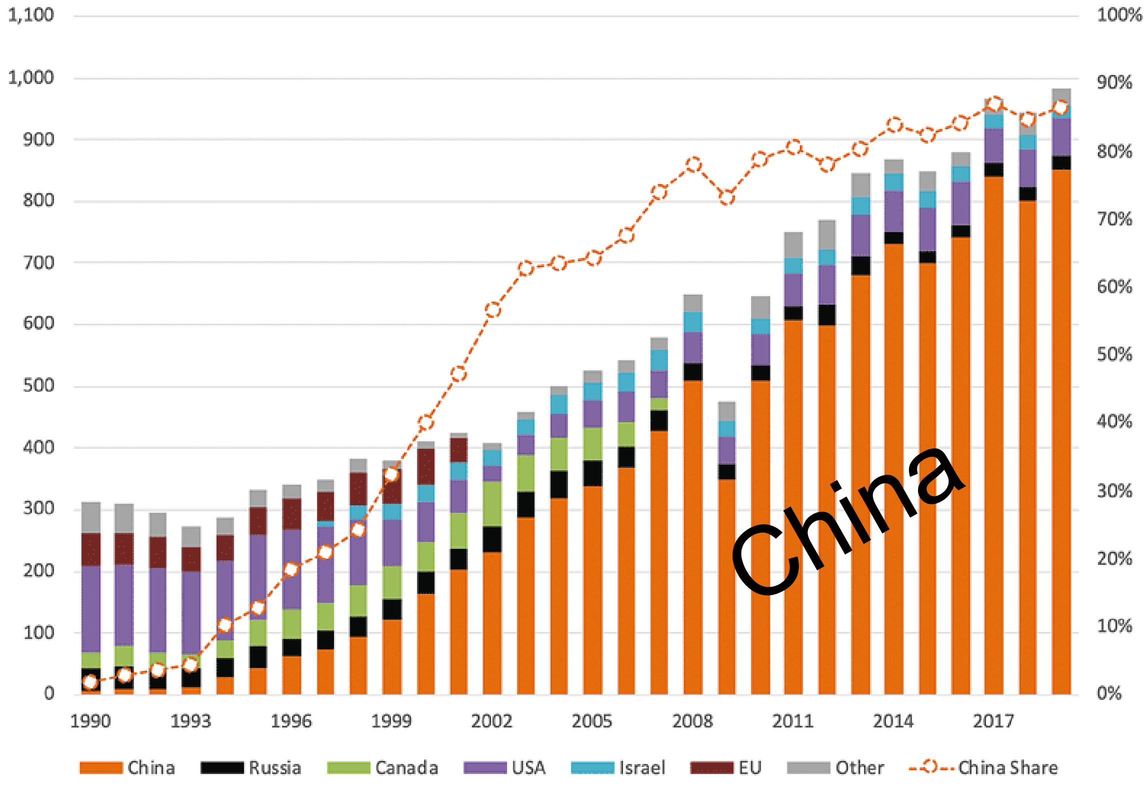
- Broader industrial application remains limited by manufacturing-related challenges
- Limited plastic formability due to the HCP crystal structure
- High raw material costs and a geopolitical production monopoly

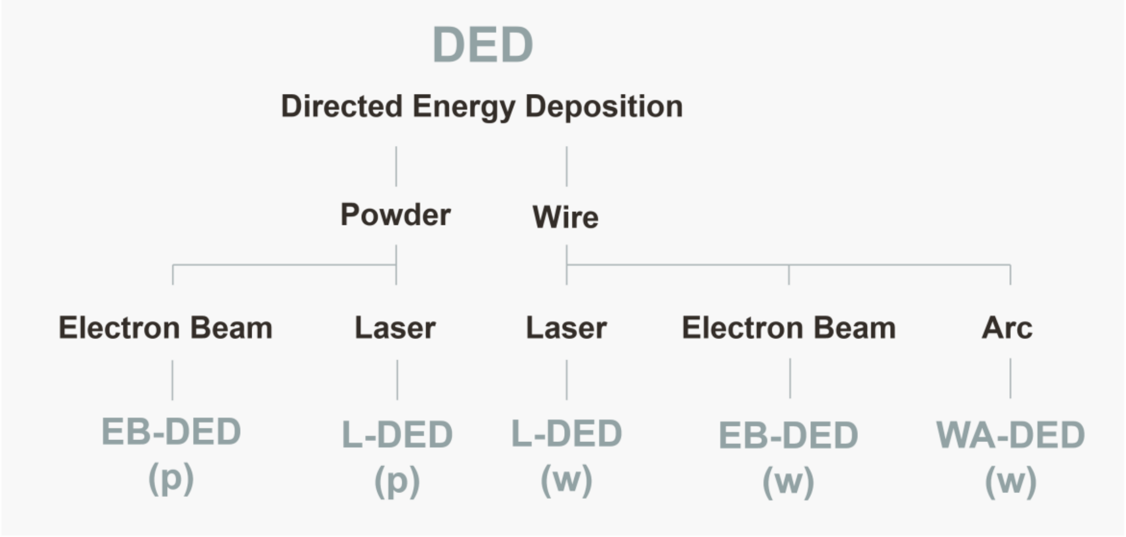


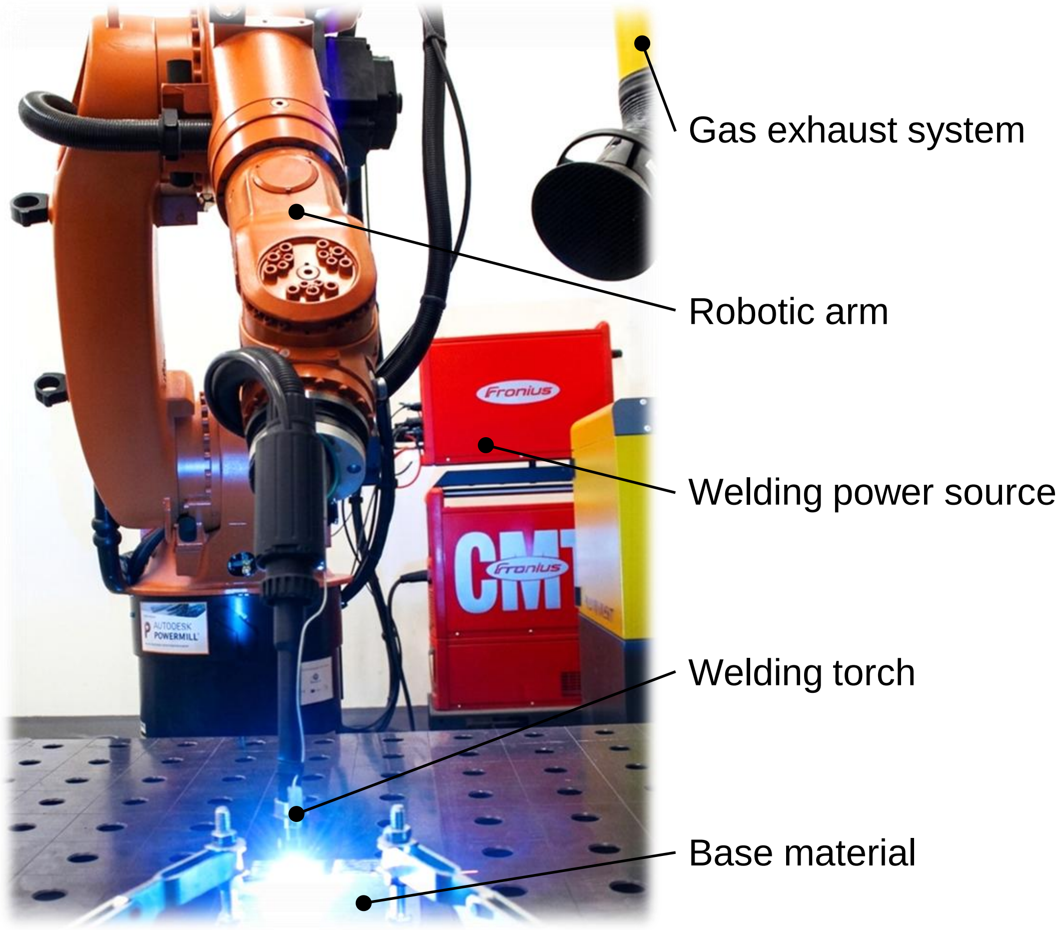
Global primary magnesium production by country - kt (energyindustryreview.com)

State of the Art – Wire Arc Directed Energy Deposition

Wire Arc Directed Energy Deposition

- Robotic arm + welding power source
- Low capital and operational costs combined with high productivity
- Fronius 2005 – technology Cold Metal Transfer
- Improved electric arc stability and low heat input





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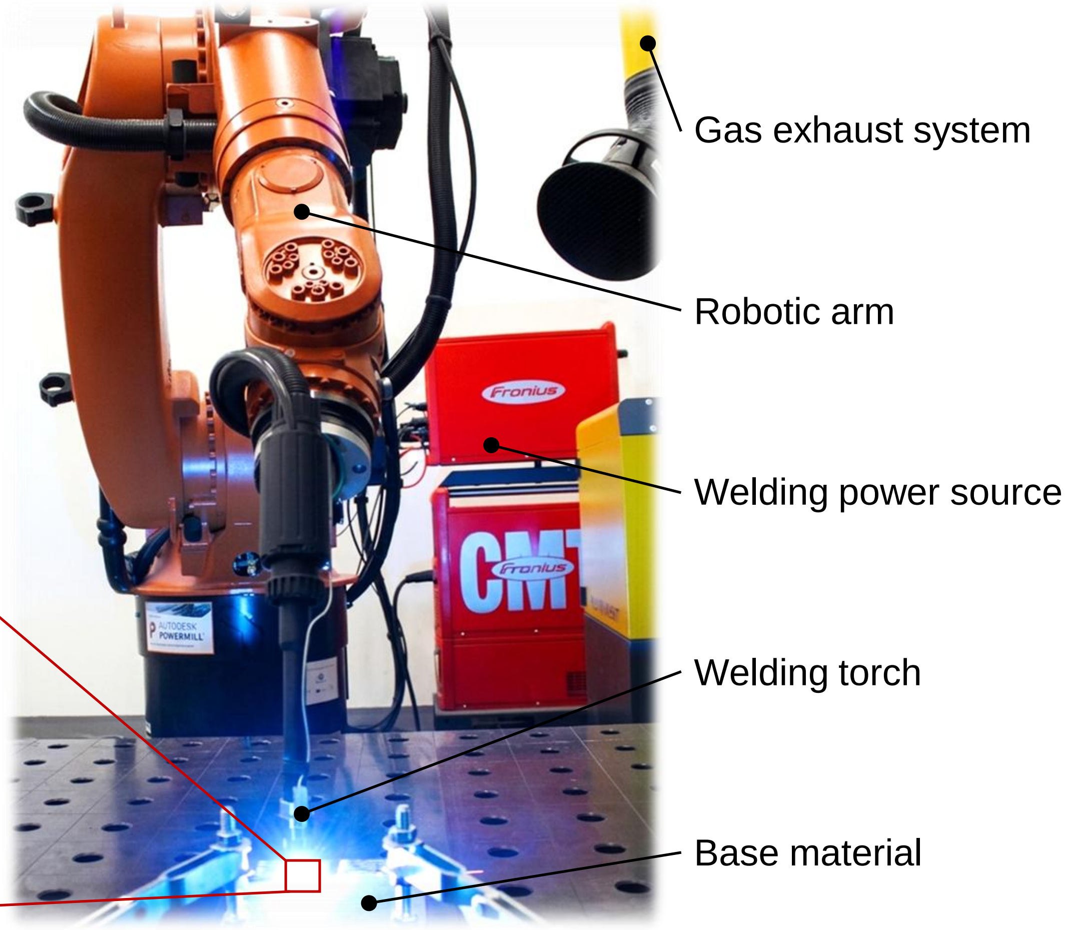
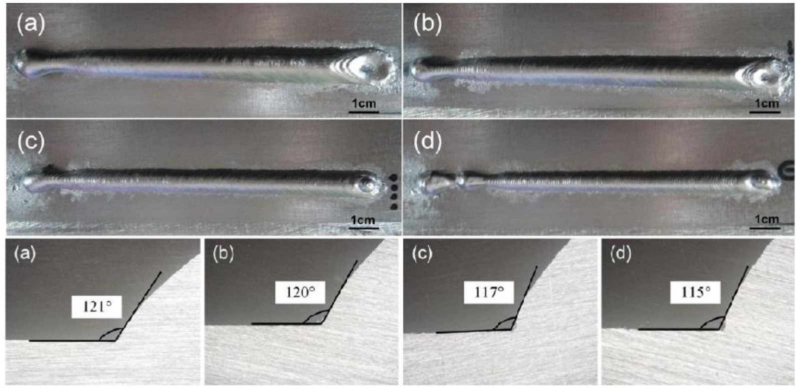


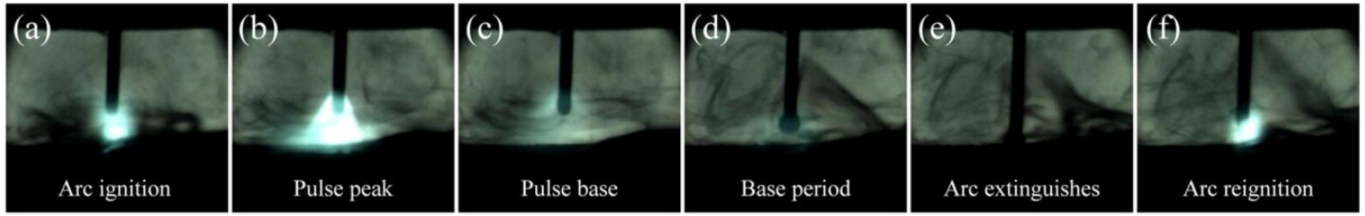
State of the Art – WADED magnesium alloy

2015 — 2020 — 2021

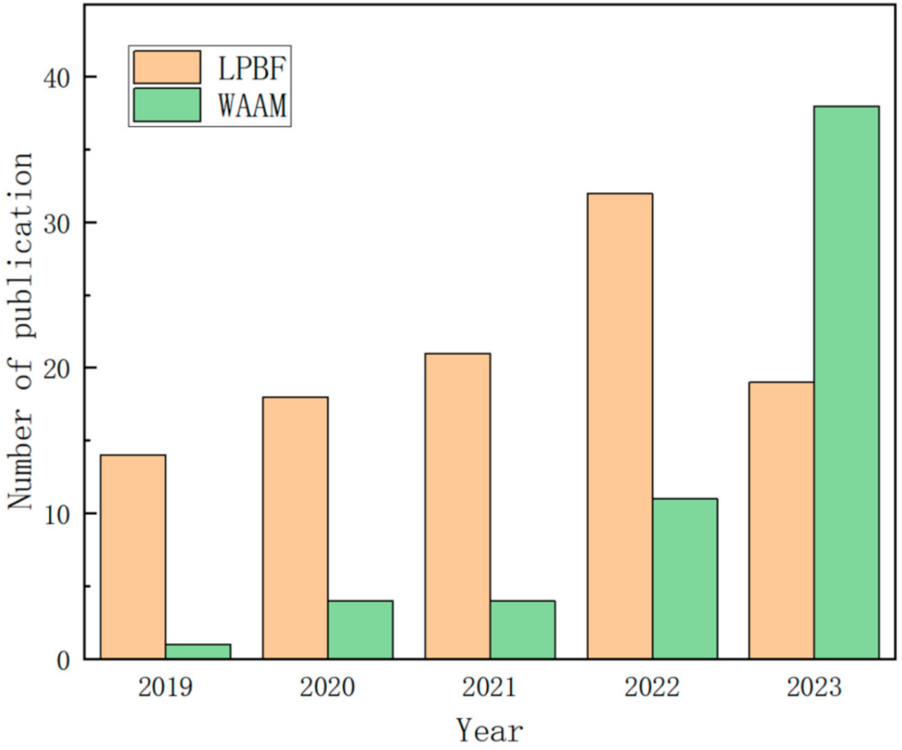
Zhang, H. et al.; Chen, J. et al.

- The effect of welding speed on microstructures of AZ31 alloy
- Welding speed 8–14 mm·s^{-1}
- Slow – liquidation crack
- Fast – excessive porosity
- Best properties 10–12 mm·s^{-1}





Publication trends in additive manufacturing of Mg alloys



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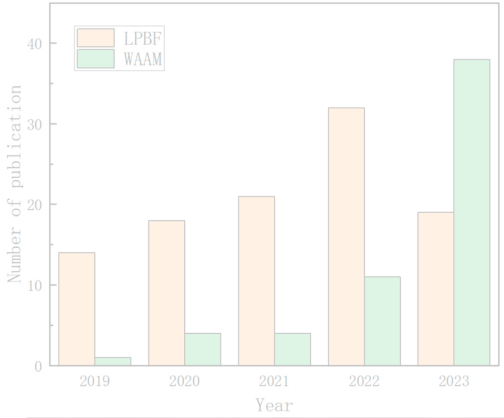
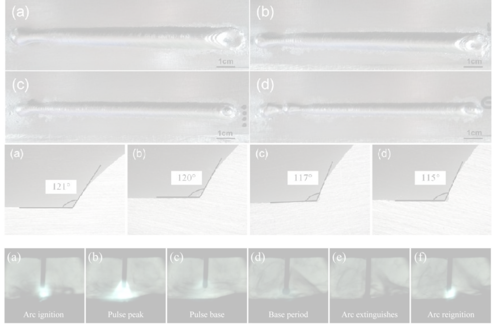
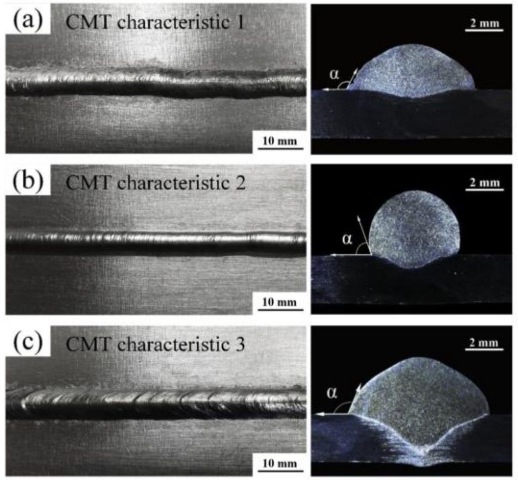
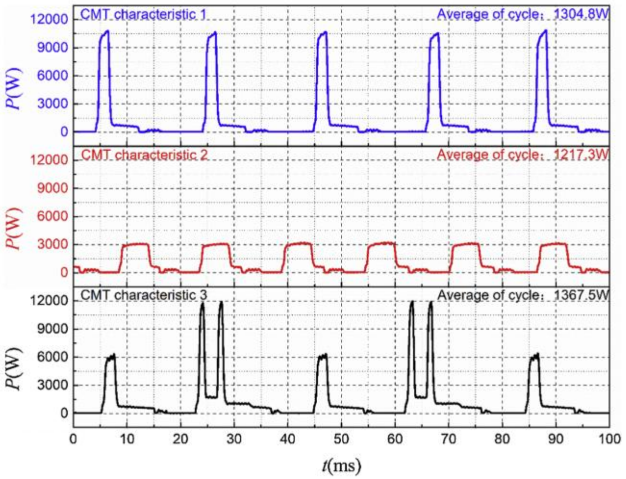


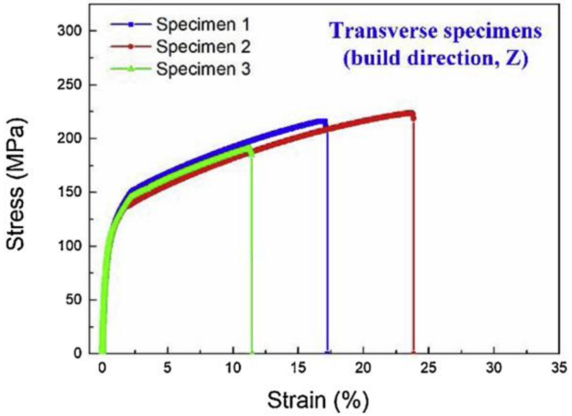


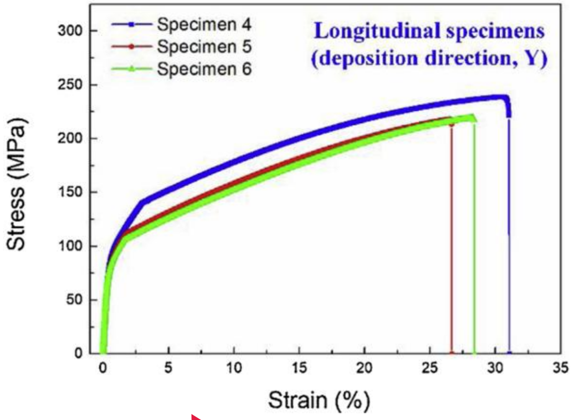
Wang, P. et al.

- The effect of CMT characteristics on weld behaviour AZ31
- Deposited layer fine columnar grains, HAZ coarsed equiaxed grains
- Anisotropic mechanical properties YS (85.4–129,5 MPa)





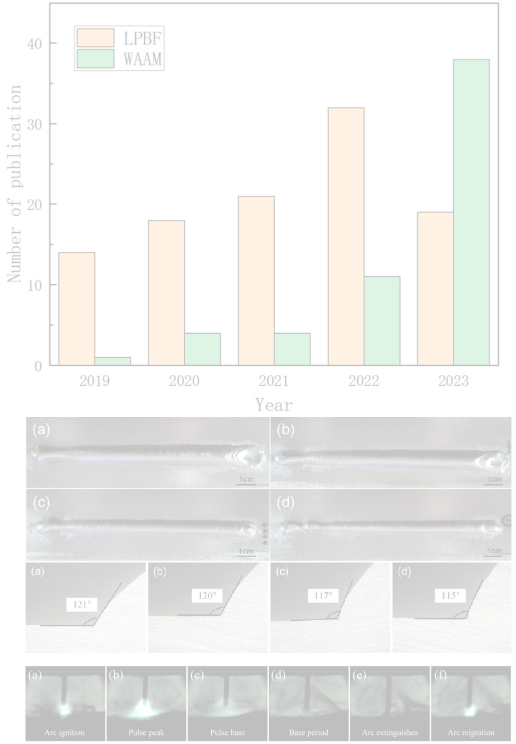




State of the Art – WADED magnesium alloy

2015 — 2020 — 2021

Zhang et al.; Chen et al.



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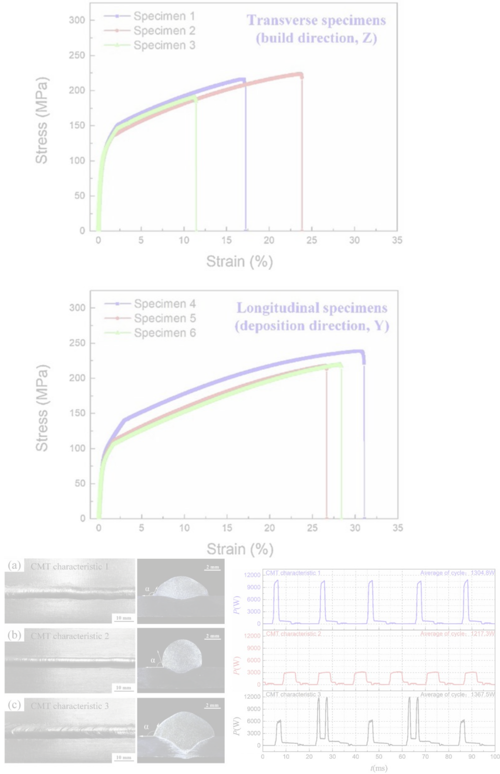
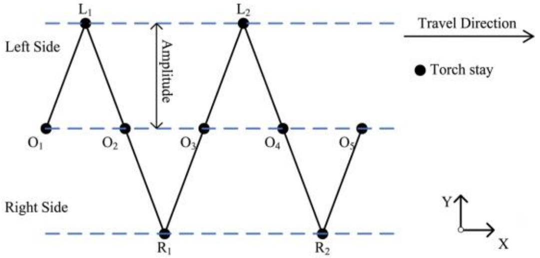
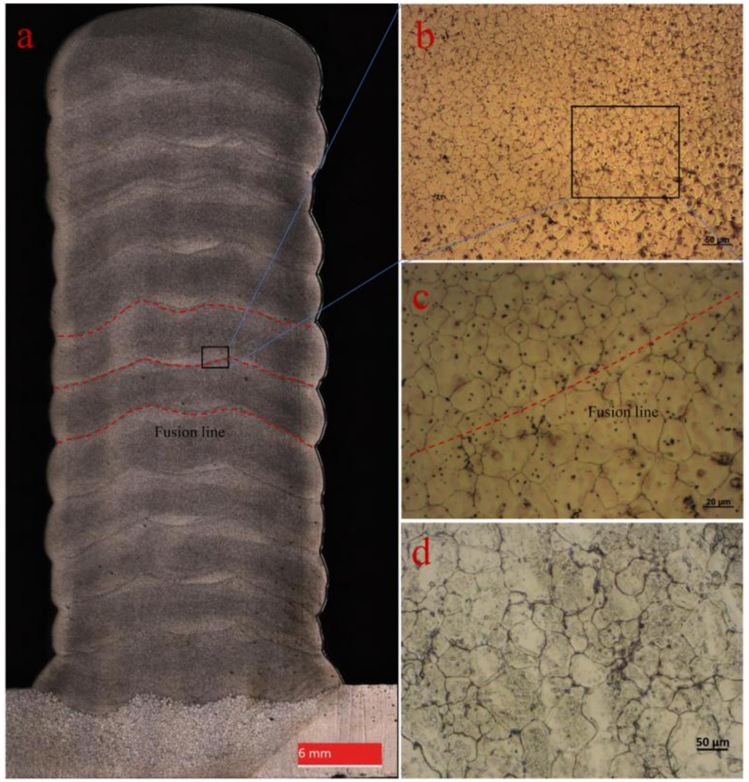


Bi, J. et al.

- AZ91 fabricated using CMT
- Thick wall component – triangle weaving mode
- Equiaxed grains
- Isotropic characteristics
- Mechanical performance better than castings





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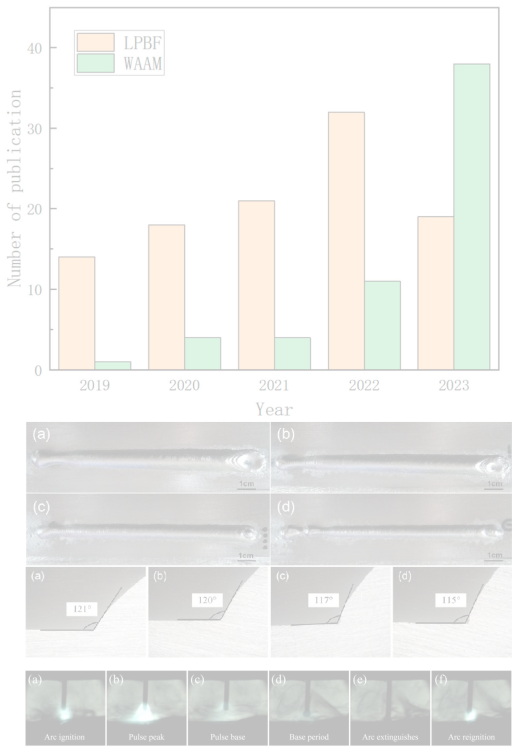

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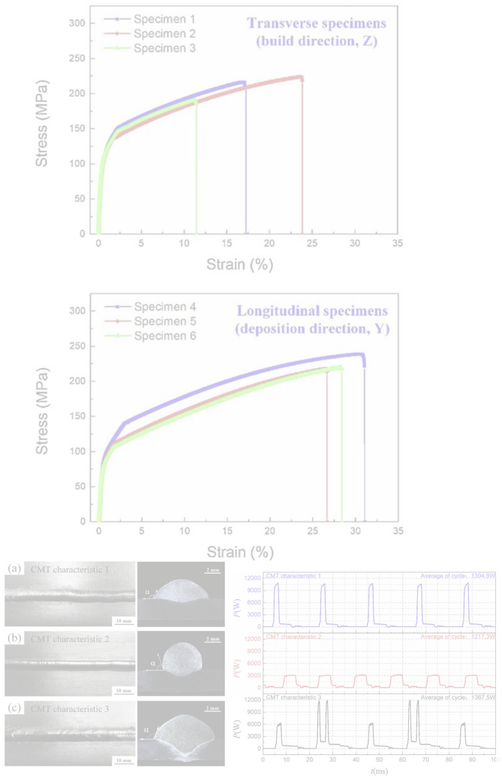

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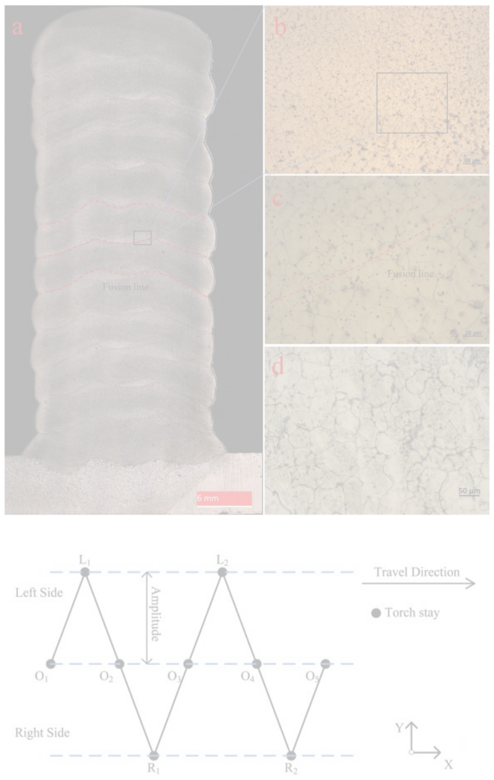
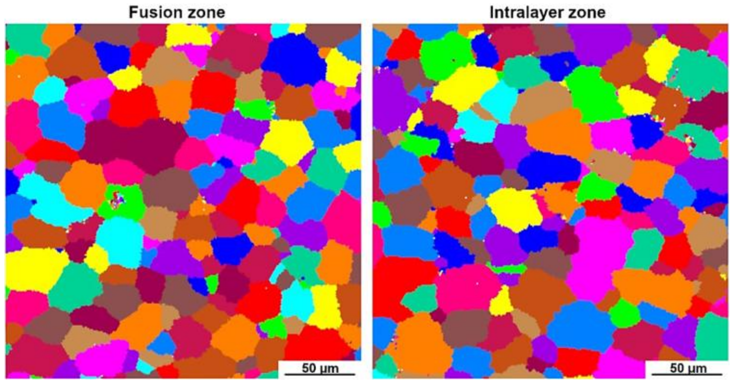


Klein, T. et al.

- AZ61 fabricated using CMT
- Homogeneous fine-grained microstructure
- YS (99–104 MPa), TS (256–264 MPa)
- Mechanical properties between typical cast and wrought magnesium alloys
- No major cracks or excessive porosity

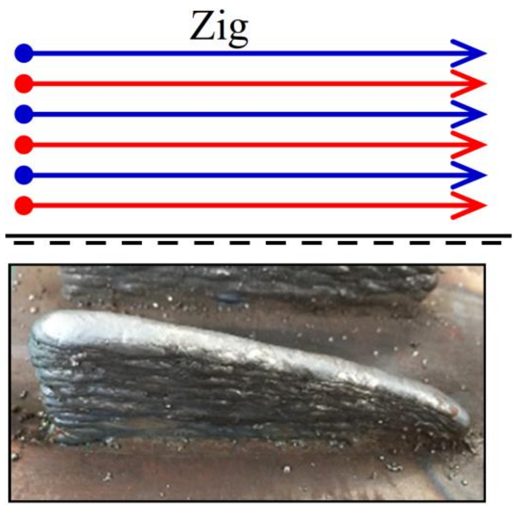


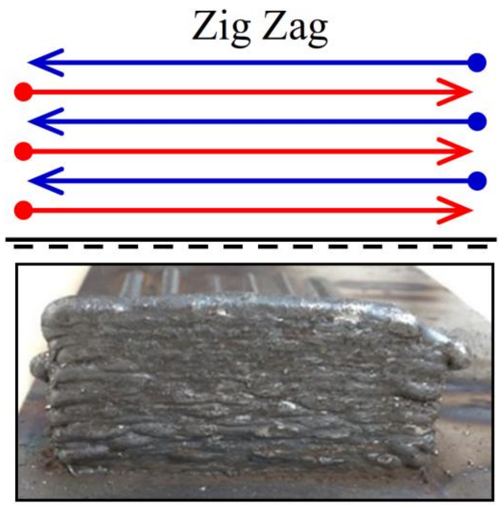
State of the Art – manufacturing strategies

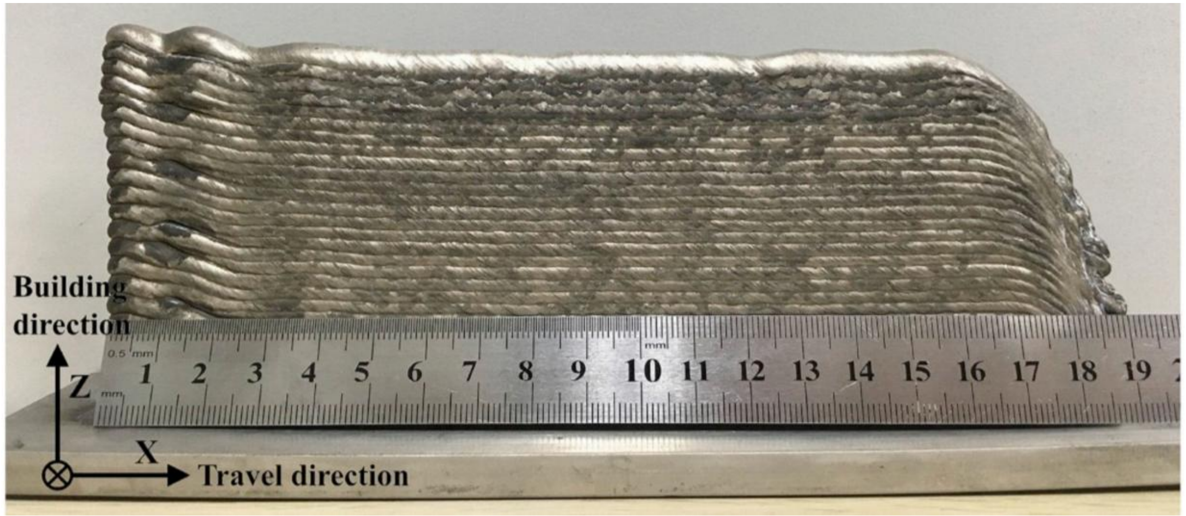
2017 — 2019 — 2021

Hu, Z. et al.; Yang, X. et al.

- Weld starts and ends associated with excessive or insufficient bead height
- Local geometric deviations accumulate during layer-by-layer fabrication
- Alternating weld start and end locations promote a more uniform layer height





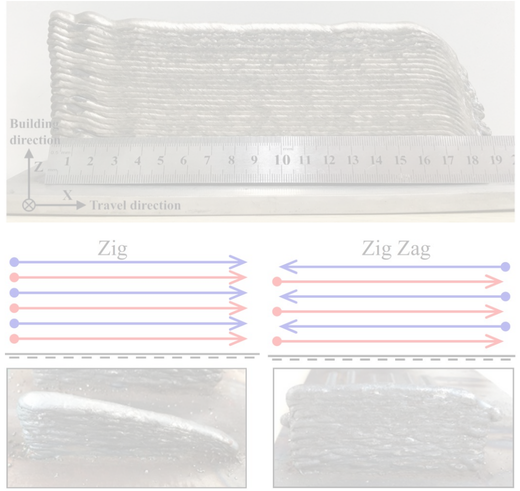


State of the Art – manufacturing strategies

2017 | 2019 | 2021

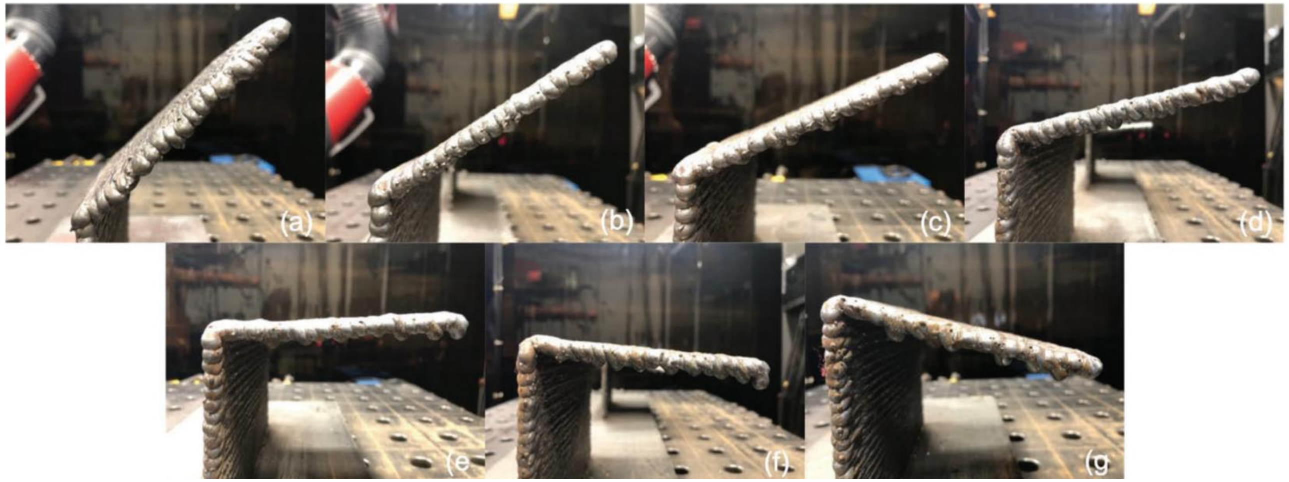
Hu et al.; Yang et al.

- Excessive or insufficient bead height
- Deviations accumulate



Plangger, J. et al.; Penney, J. et al.

- Thermal evolution of the part influences geometrical accuracy and waviness
- Initial transient stage (the first 10-15 layers) and a steady state stage
- Welding torch orientation plays a crucial role for overhangs
- Fabrication of inclined walls possible but challenging



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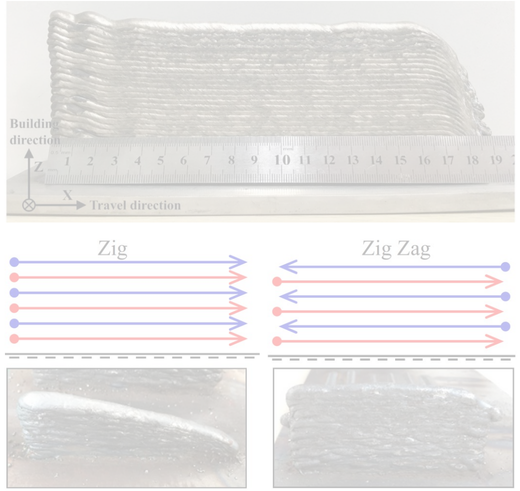

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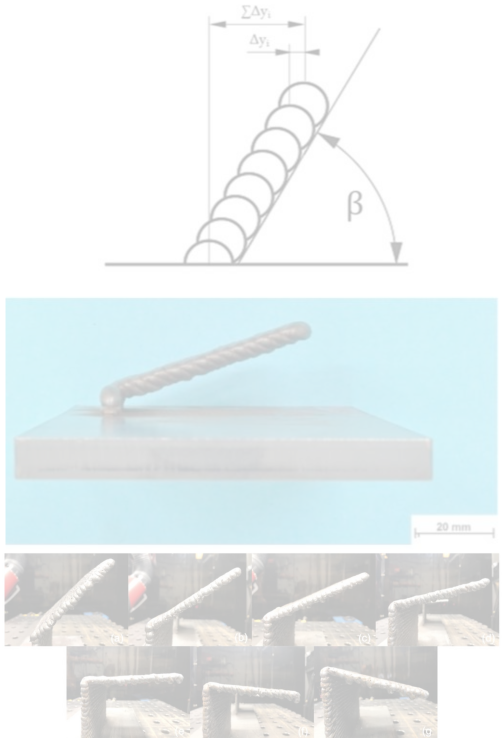
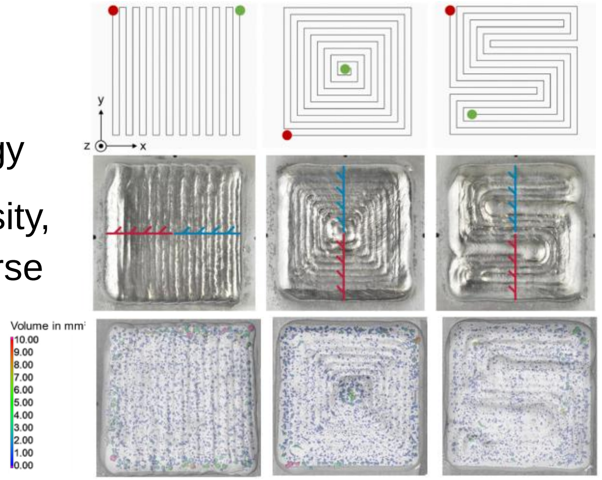
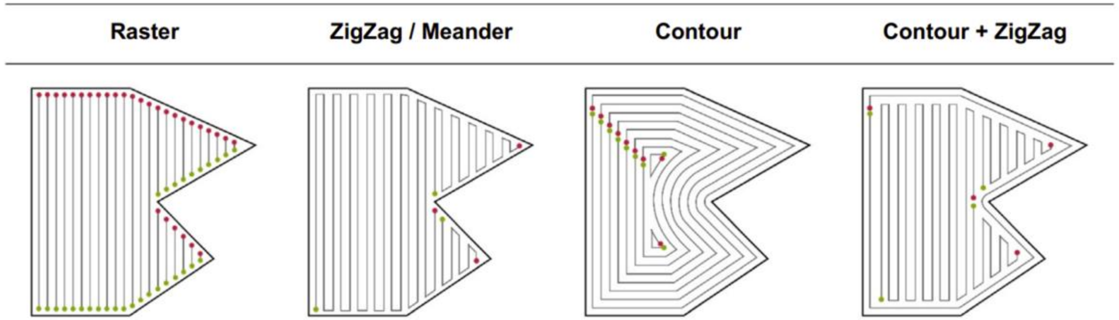


Köhler, M. et al.

- Temperature distribution strongly dependent on the deposition strategy
- S-pattern can lead to reduced porosity, low residual stress and smaller coarse grain size
- Local residual stress peaks at the end of the deposition pattern

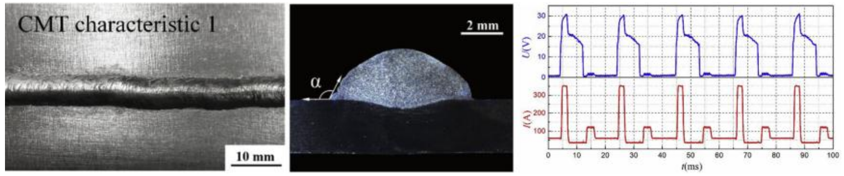




Summary of literature review

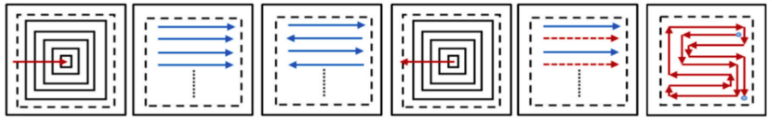
Key process-related factors for magnesium alloy

- ✓ Different CMT parameter sets reported
- ✓ Most common alloys AZ31, AZ91, AZ61
- ✓ Magnesium's high reactivity and thermal sensitivity



Deposition path planning

- ✓ Weld bead start – excessive, end – insufficient material deposition
- ✓ Suppressing deformations – bead sequencing
- ✓ Volumetric parts – different cooling rates, material accumulation



Thermal management

- ✓ Faster cooling rates – finer microstructure
- ✓ Lower temperature gradients – less residual stresses

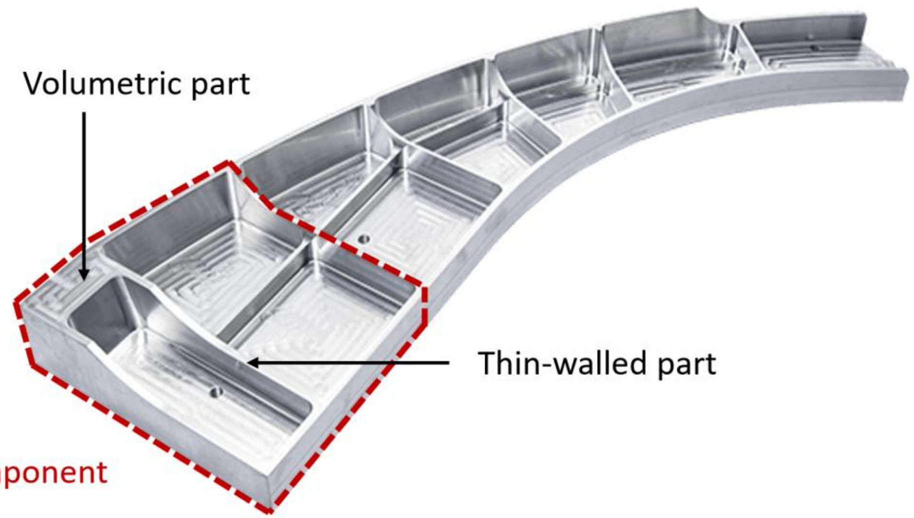
Knowledge gaps

- Bead sequencing strategies – residual stress, start and end irregularities
- Systematic analysis of CMT parameters – bead geometry, process stability
- Preheating and interpass temperature – microstructure and residual stress
- Fabrication of volumetric samples

Aim of the thesis

The main goal of the thesis

The thesis aims at optimisation of WADED process parameters and strategies for producing high-quality structured components from magnesium alloys.



The benefit of the thesis

- Describing the effects of key process-related factors – simplifying development for further magnesium-based materials
- Methods for reducing deposition and thermal defects
- Tailoring microstructure and mechanical properties

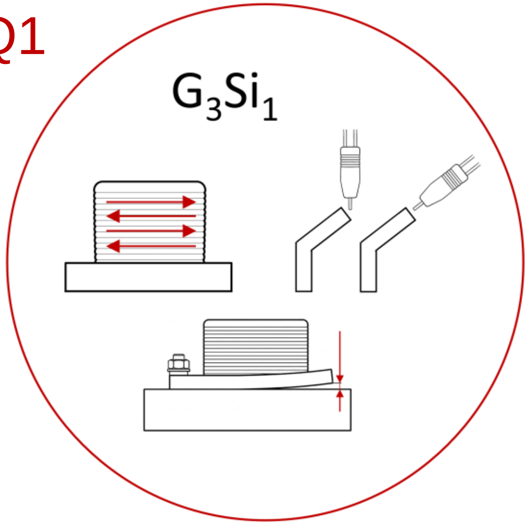
Application potential

Optimise process: parameters, strategies, properties ⇨ Improve BTF, manufacturing route for lightweight parts ⇨ Reduce weight of aircraft, eco-impact of transportation

Scientific question and hypothesis

Stage I.

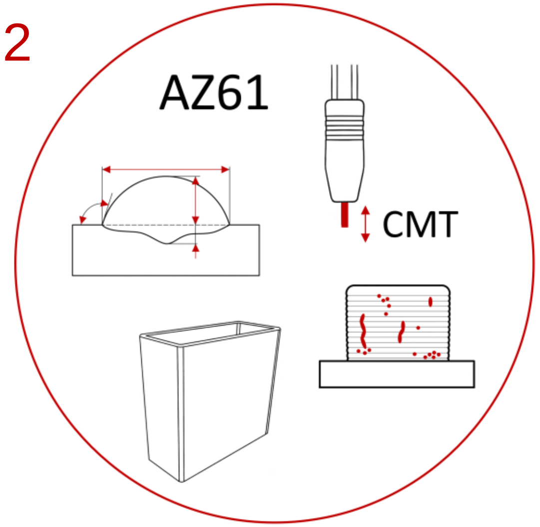
Q1



Thin-wall strategy

Stage II.

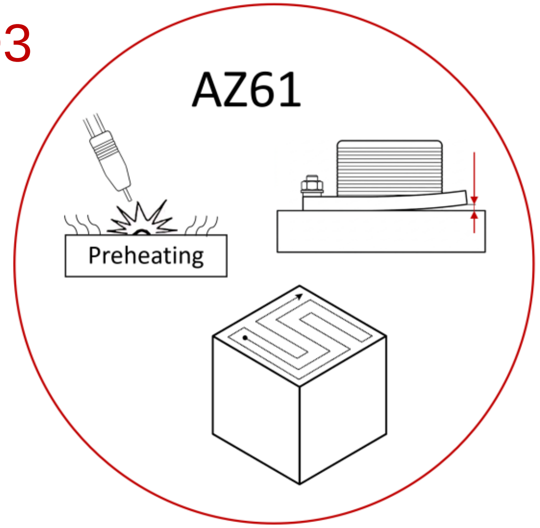
Q2



Defect free AZ61

Stage III.

Q3



Thermal management

Scientific question and hypothesis

Scientific questions

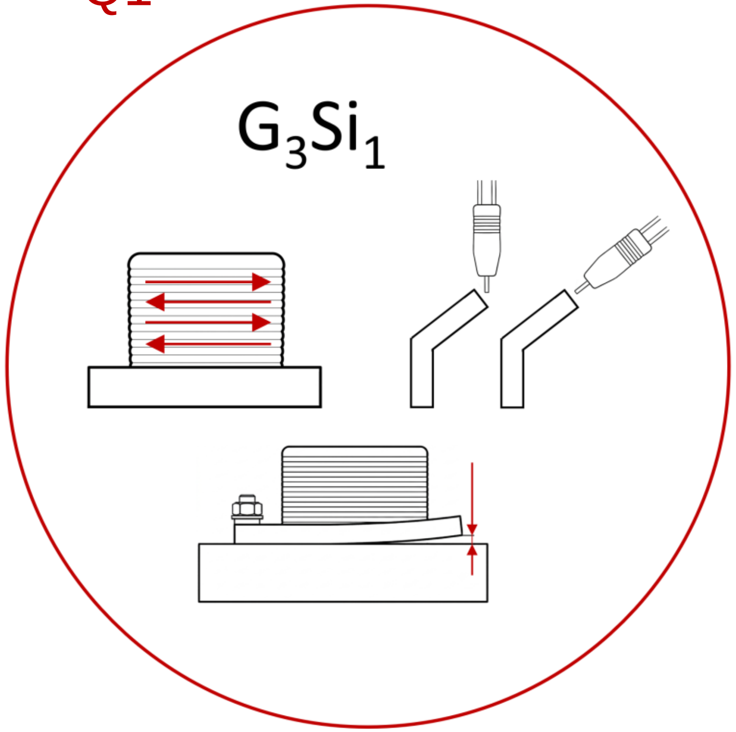
Q1: How does deposition path planning influence the geometrical accuracy and residual stress?

Hypotheses

H1a: Deposition strategies that redistribute weld start and end locations along the component length promote a more uniform layer height and improved geometrical stability.

H1b: Strategies that promote more uniform heat distribution during deposition are expected to reduce the residual stresses in thin-walled components.

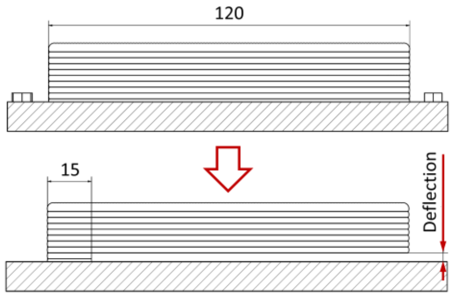
Q1

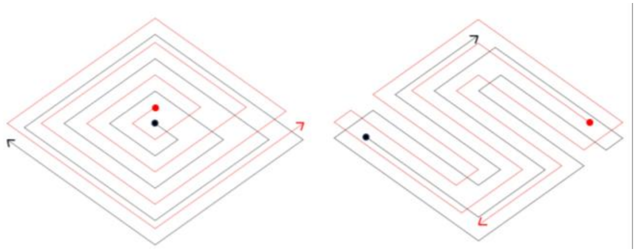


Materials and methods – Q1

Material
- Base material – S235JR
- Filler material – G3Si1

Sample type
- Thin-walled sample
- Volumetric sample
- Overhang sample

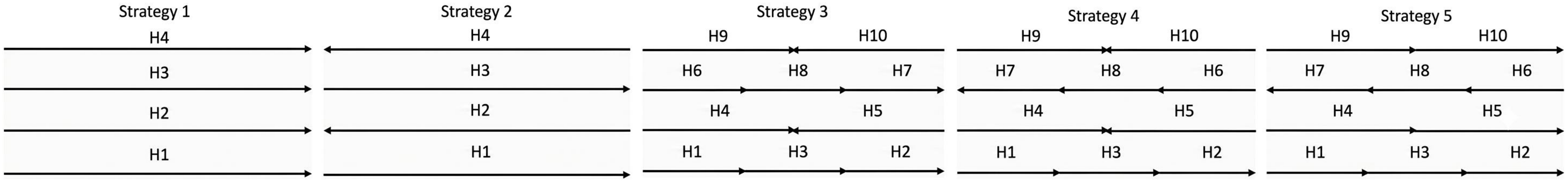




Analysis
- Dimensional accuracy (3D scanning)
- Residual stress – indirect analysis (deflection)

Desired output
- Height deviation
- Residual stress comparison
- Angle deviation

Experimental setup development
- Newly established CMT-WADED lab

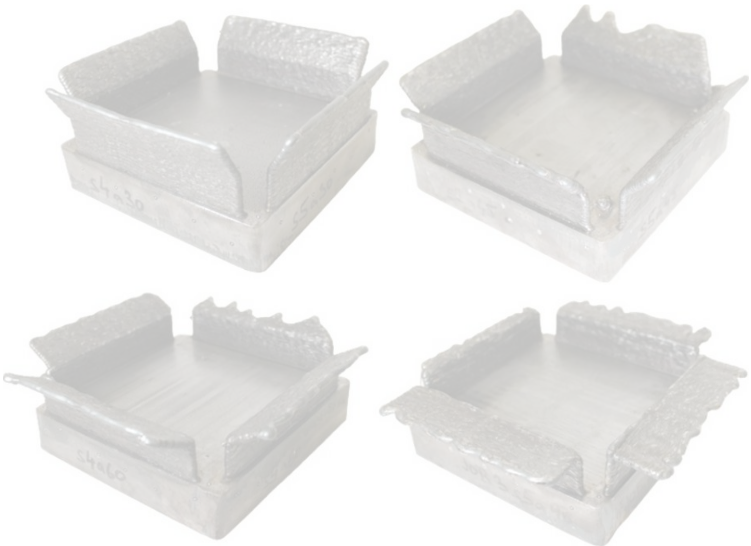


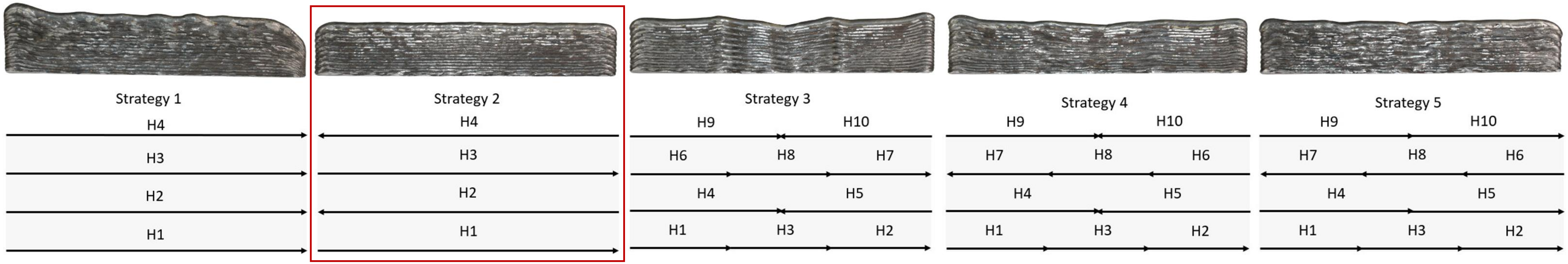
Results and Discussion

Scientific question 1 – Deposition path planning (dimensional accuracy H1a)

Fabrication parameters

- Material – G3Si1, Shield gas CO_2+Ar
- Travel speed – 5 $mm \cdot s^{-1}$, wire feed rate – 5 $m \cdot min^{-1}$
- Five different production strategies
- Weld bead start and end locations are critical for production accuracy
- Even more critical for overhangs and challenging materials





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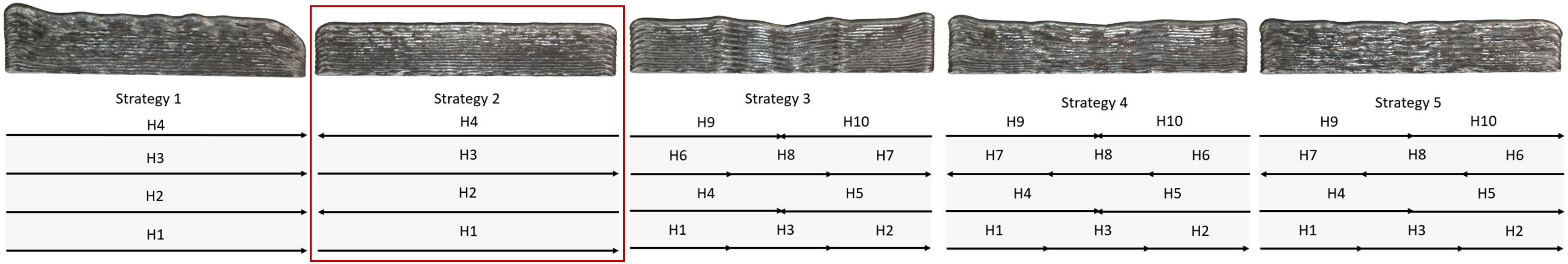
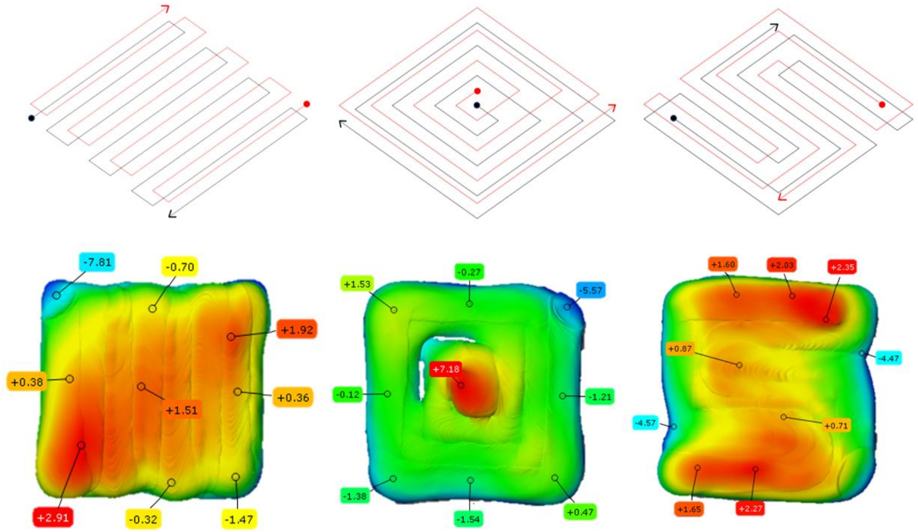


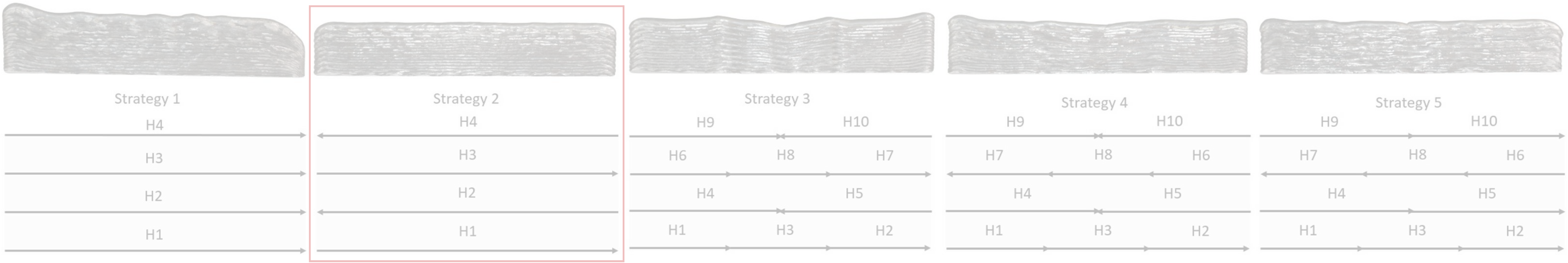
Results and Discussion

Scientific question 1 – Deposition path planning (dimensional accuracy H1a)

Fabrication parameters

- Material – **AZ61**, Shield gas Ar
- Travel speed – 15 mm·s^{-1}, wire feed rate – 10 m·min^{-1}
- Five different production strategies
- Weld bead start and end locations are critical for production accuracy
- Even more critical for overhangs and **challenging materials**





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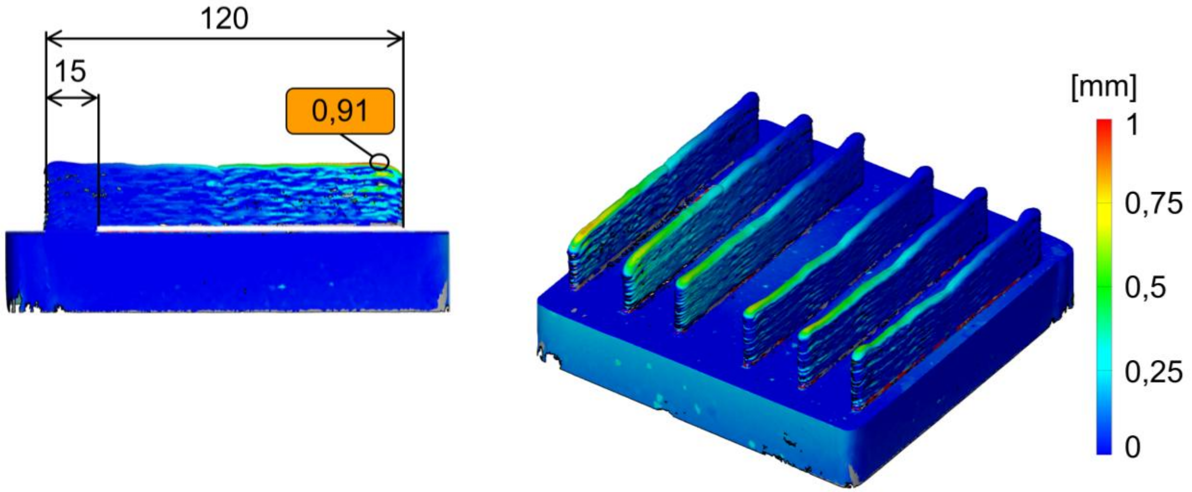
Results and Discussion

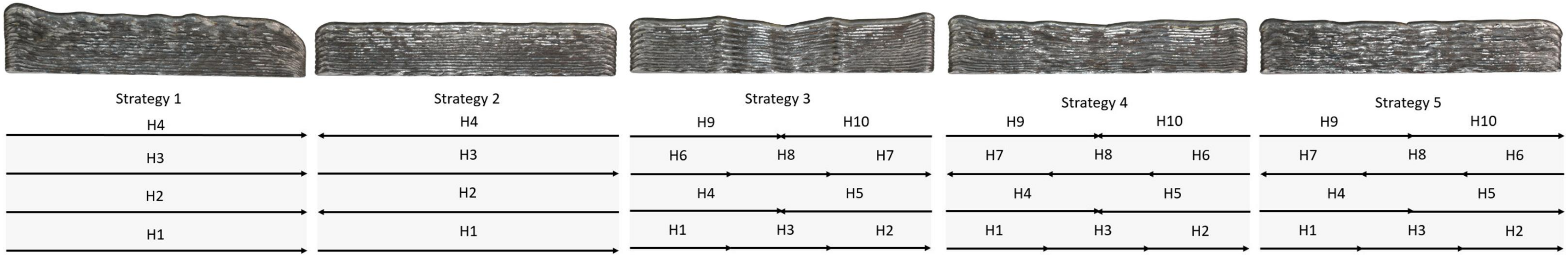
Scientific question 1 – Deposition path planning (residual stress H1b)

Fabrication parameters

- Material – G3Si1, Shield gas CO_2+Ar
- Travel speed – 5 mm·s^{-1}
- Wire feed rate – 5 m·min^{-1}

Strategy 1	Strategy 2	Strategy 3	Strategy 4	Strategy 5
0.35 mm	0.67 mm	0.91 mm	0.56 mm	0.79 mm





Conclusions

Evaluation of scientific questions

Q1: How does deposition path planning influence the geometrical accuracy and residual stress?

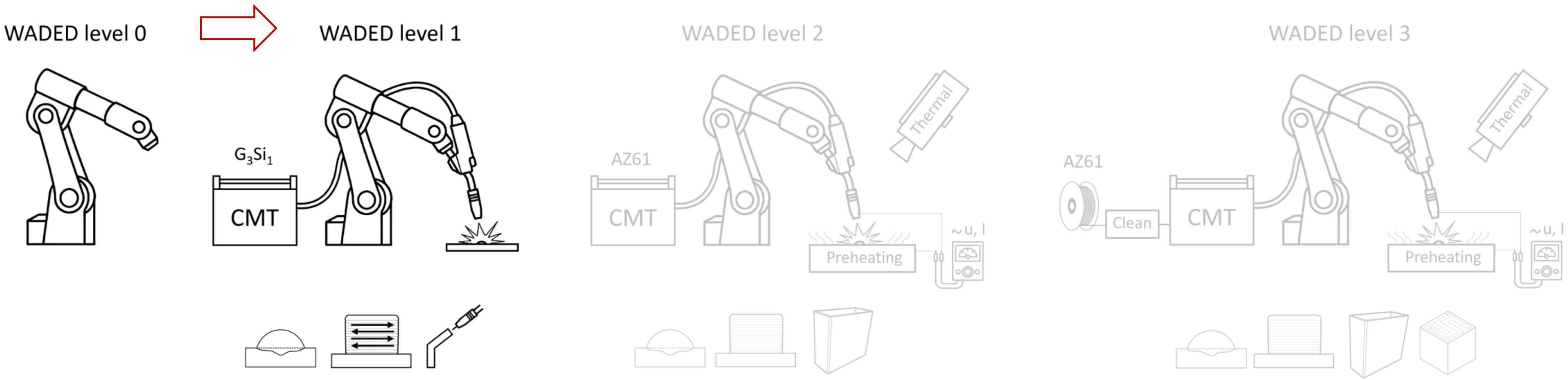
- Path planning strategies significantly influence components' geometrical accuracy
- Suitably redistributed weld starts and ends effectively mitigated excessive material accumulation
- Welding sequences did not exhibit any consistent trend indicating a reduction in residual stress levels

H1a hypothesis

Not falsified

H1b hypothesis

Falsified



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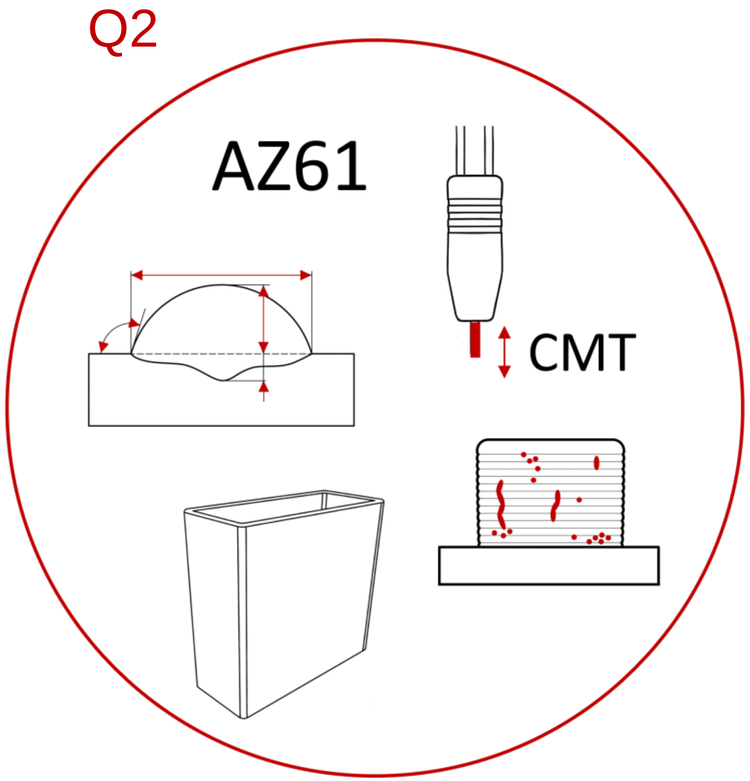
Scientific question and hypothesis

Scientific questions

Q2: What are key process-related factors and how do they affect process stability and defect formation during WADED of AZ61 magnesium alloy?

Hypotheses

H2: Proper control of main CMT parameters is expected to stabilise the melt pool, reduce porosity, and enable the fabrication of thin-walled components with a relative material density exceeding 99%.



Materials and methods – Q2

Material

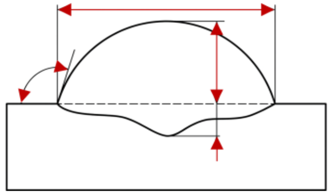
- Base material – AZ91, AZ31
- Filler material – AZ61

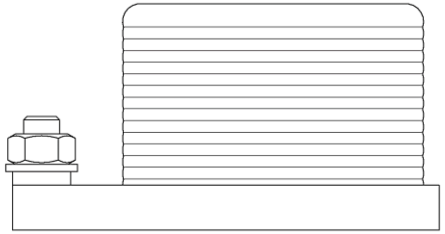
Sample type

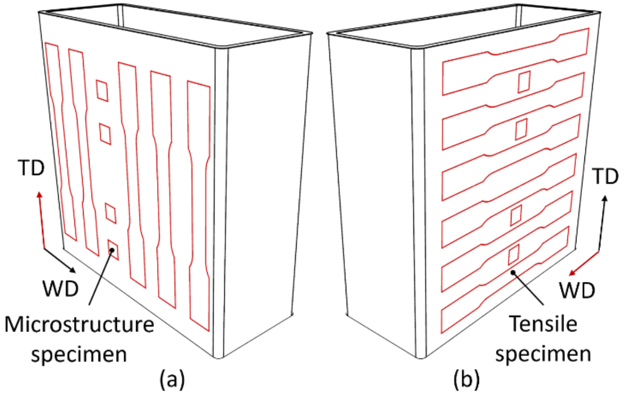
- Single-track sample
- Thin-walled sample

Analysis

- Dimensional accuracy
- Metallography
- SEM+EDS analysis
- Porosity
- Tensile testing





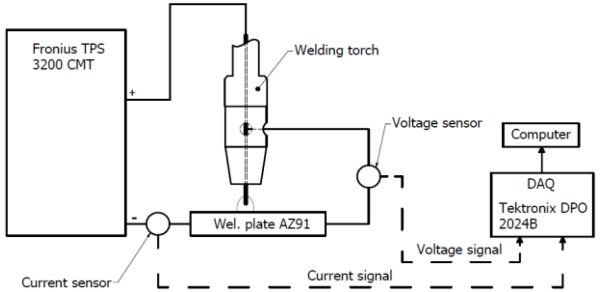


Desired output

- Single track geometry
- Microstructure
- Chemical composition
- Mechanical properties

Experimental setup development

- Filler wire cleaning manually + I. gen
- Preheating table + thermal camera
- CMT characteristic measurement (u, I)

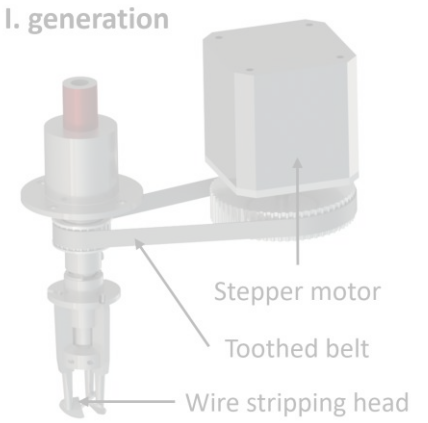


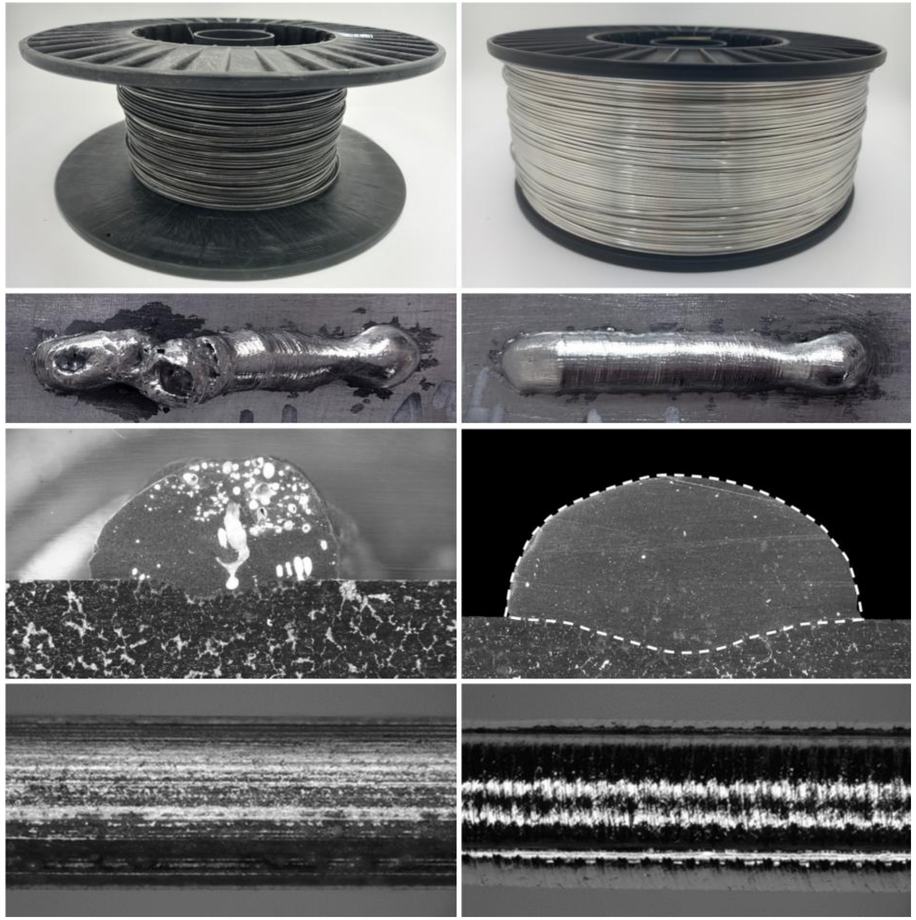
Results and Discussion

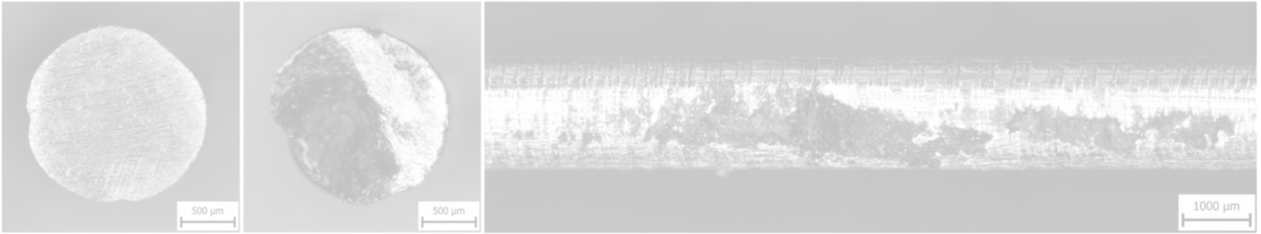
Scientific question 2 – key process-related factors (H2)

Filler wire quality, CMT parameters, preheating

- Magnesium alloy AZ61 wire, diameter 1.6 mm
- Oxide layer (electrical resistance), hydroxides (porosity)
- Wire surface cleaning necessary
- Manual cleaning with sandpaper
- I. generation + heat treatment







Results and Discussion

Scientific question 2 – key process-related factors (H2)

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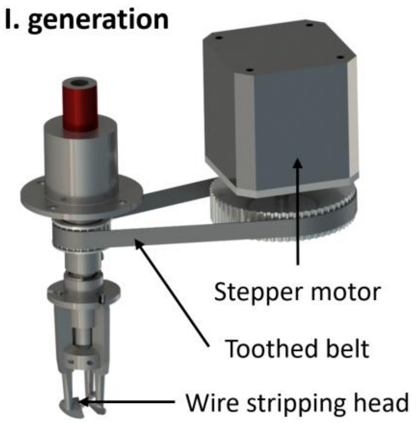
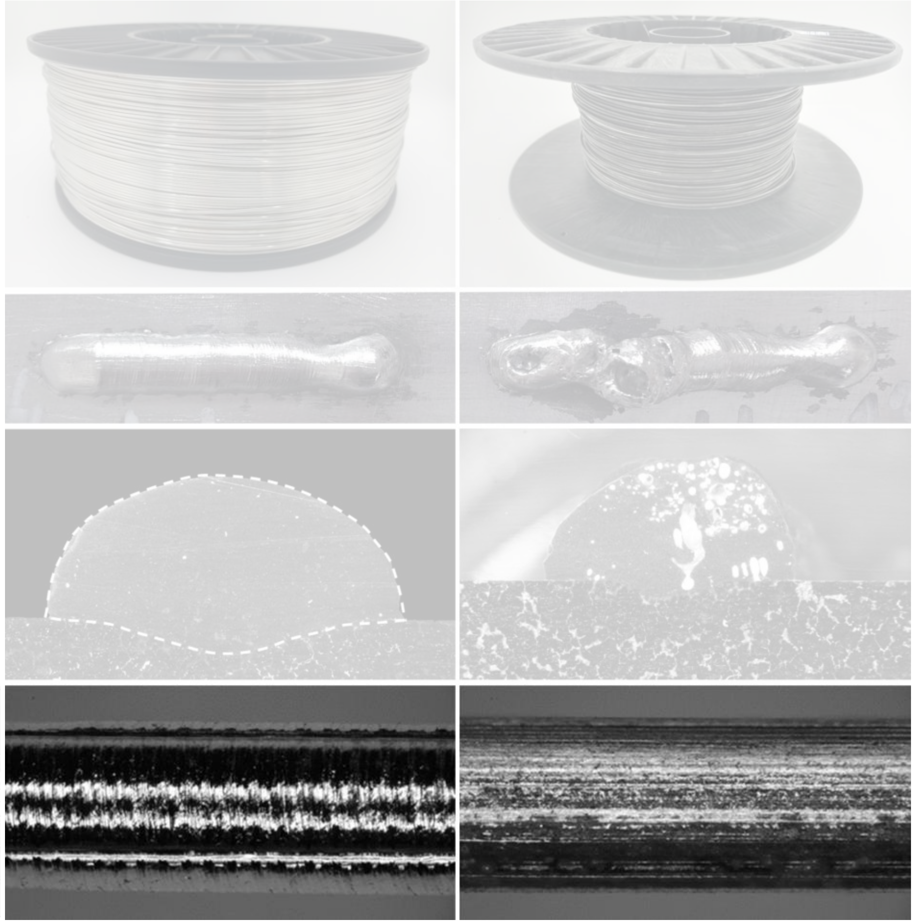
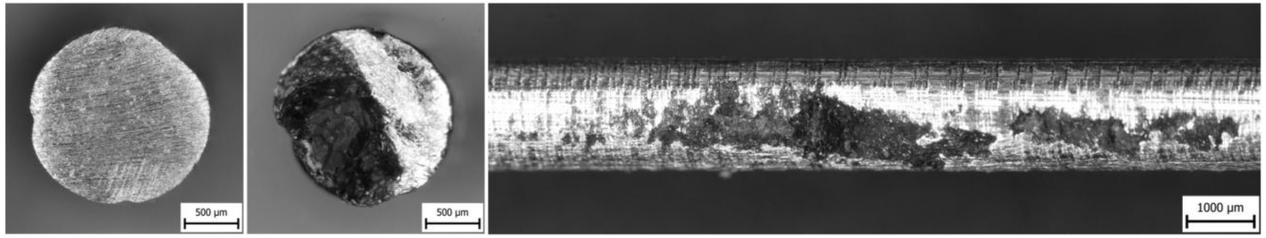




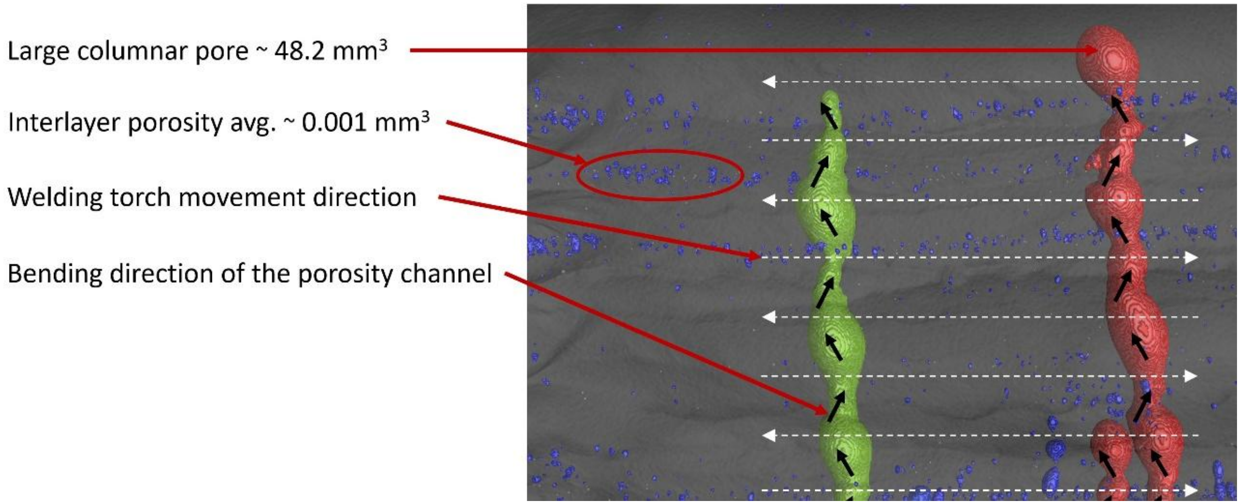


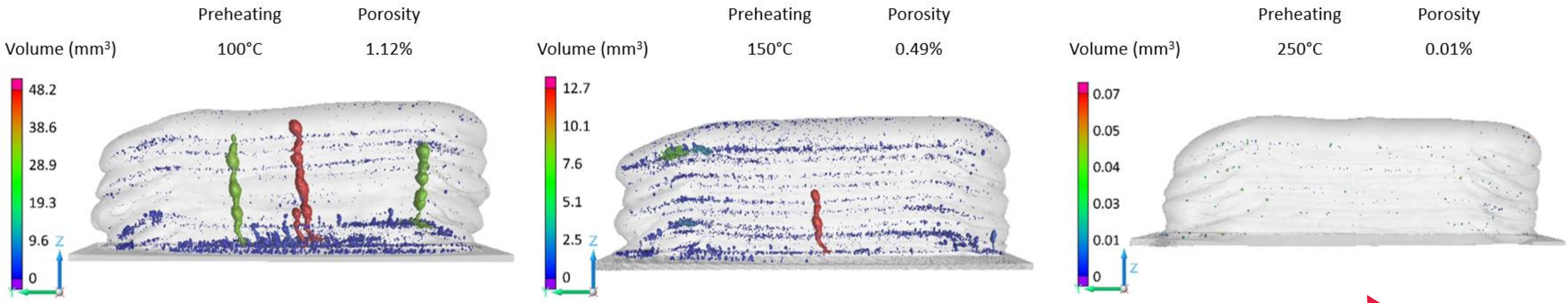
Results and Discussion

Scientific question 2 – key process-related factors (H2)

Filler wire quality, CMT parameters, **preheating**

- Preheating temperatures 50–300 °C
- Large columnar porosity
- Hydroxides on wire surface – hydrogen in melt pool
- Rapid solidification – gas trapped as pores
- Higher preheating – slower cooling – time to escape





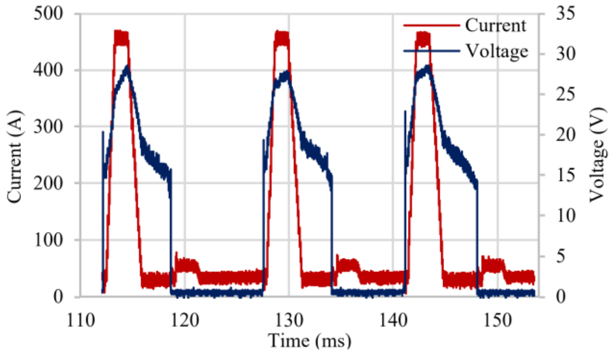
Results and Discussion

Scientific question 2 – key process-related factors (H2)

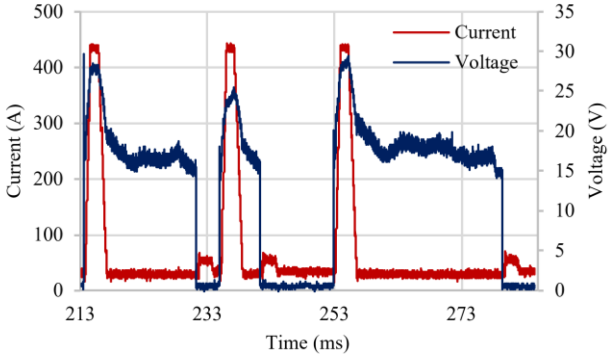
Filler wire quality, **CMT parameters,** preheating

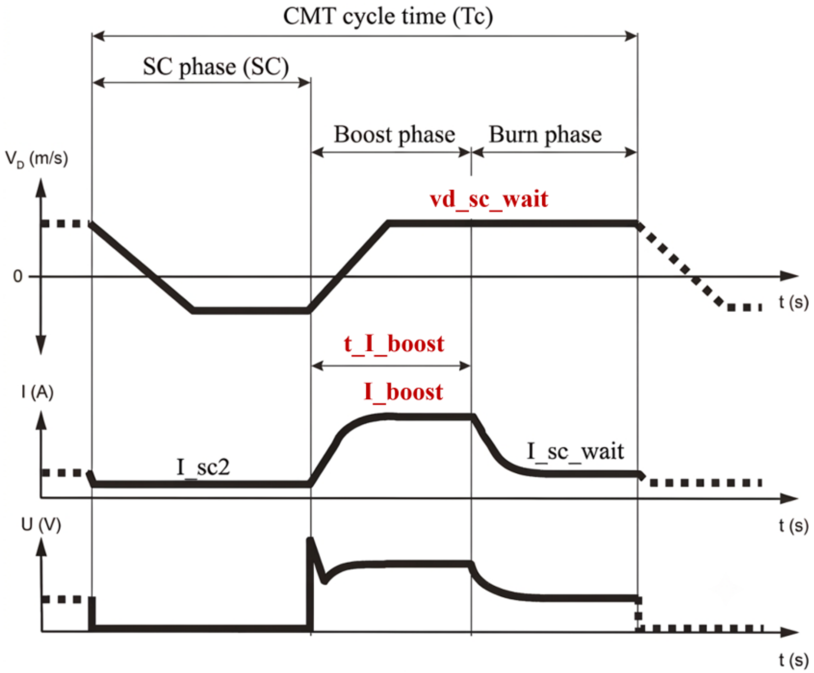
- Welding boost phase current (I_boost) and its duration (t_I_boost)
- Burn phase current (I_sc_wait), SC phase current (I_sc2)
- Electrode speed during the boost and burn phase (vd_sc_wait)

Stable CMT waveform



Unstable CMT waveform





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Results and Discussion

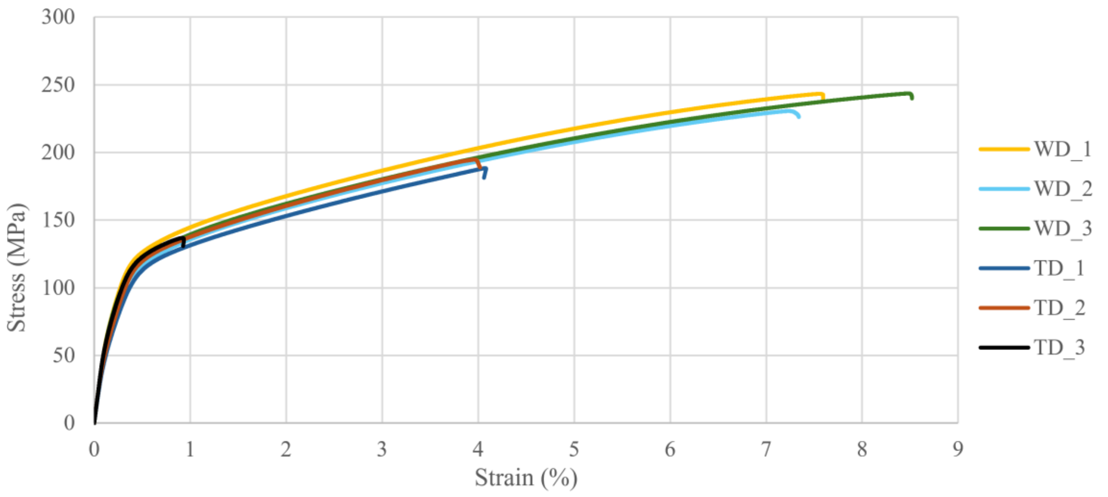
Scientific question 2 – key process-related factors (H2)

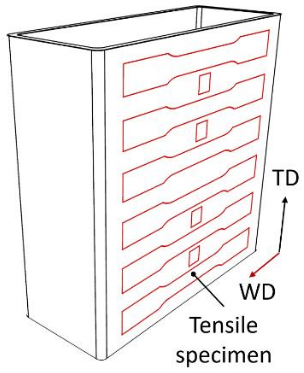
Filler wire quality, **CMT parameters,** preheating

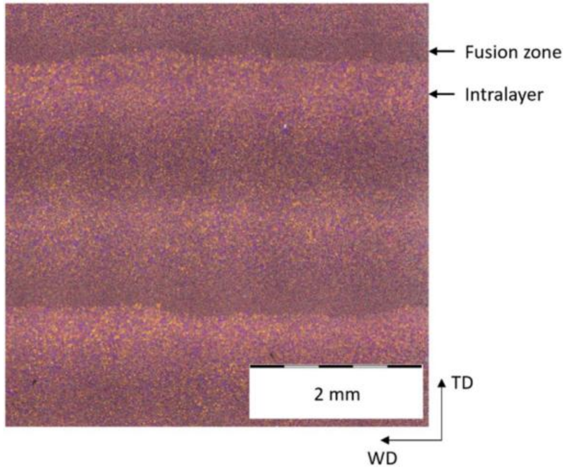
- Optimised set of parameters

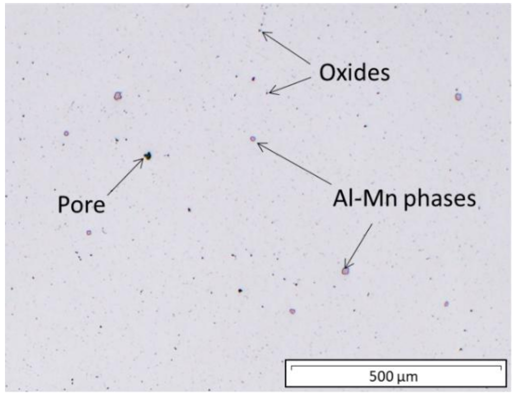
I_boost (A)	t_I_boost (ms)	I_sc_wait (A)	vd_sc_wait (m·min-1)	I_sc2 (A)
430	2.5	35	30	50

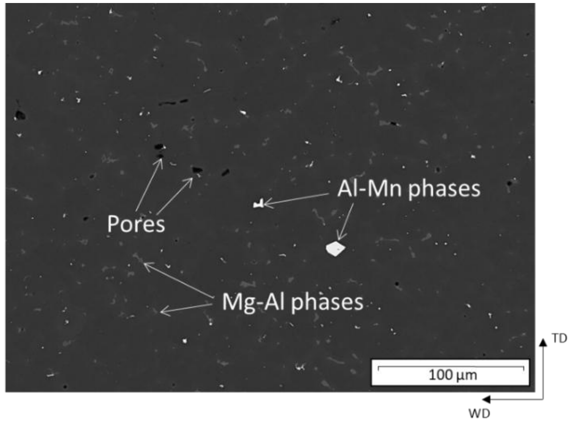
- Obvious layered microstructure, anisotropy
- Mechanical properties – UTS 239 MPa, YS 115 MPa, A 8%











Conclusions

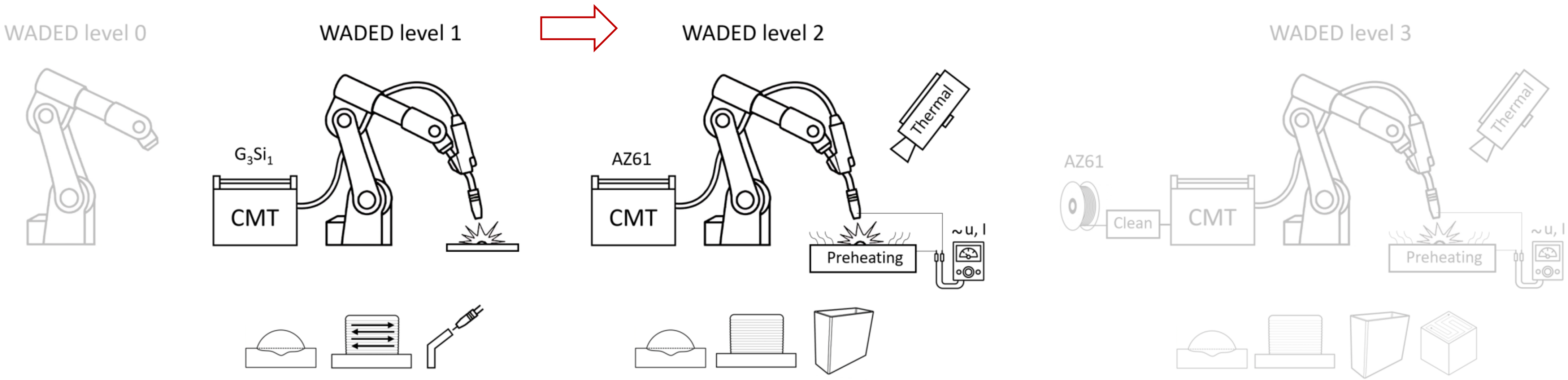
Evaluation of scientific questions

Q2: What are key process-related factors and how they affect process stability and defect formation?

- Wire surface quality was found to significantly influence welding arc stability
- Boost phase current and its duration strongly affect bead geometry, arc stability, and droplet transfer behaviour
- Increasing the preheating temperature can substantially reduce porosity formation, reaching 99.98% material density

H2 hypothesis

Not falsified



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Scientific question and hypothesis

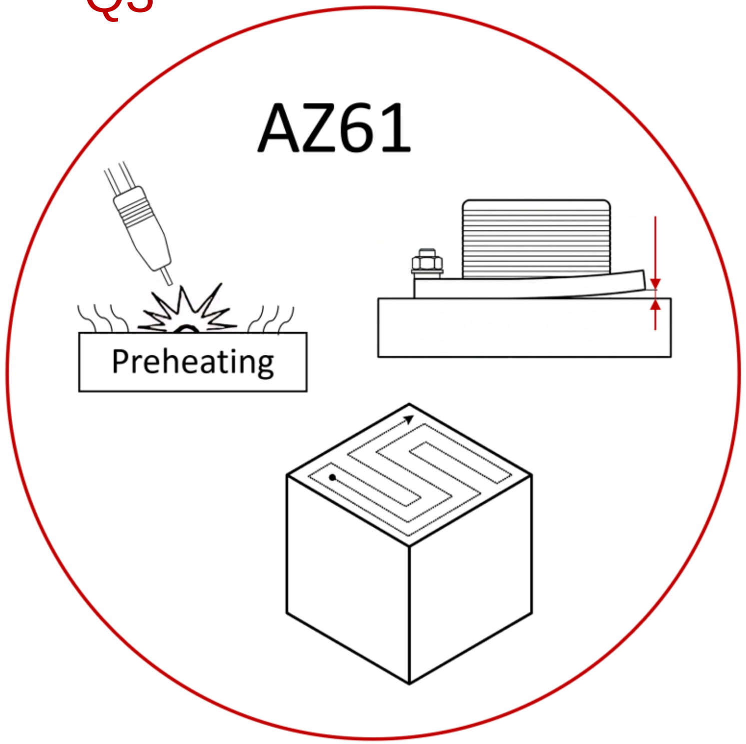
Scientific questions

Q3: How do thermal management strategies affect the development of microstructure and residual stresses during WADED of AZ61 magnesium alloy components?

Hypotheses

H3: Increasing preheating and interpass temperatures will reduce residual stresses while simultaneously promoting grain coarsening

Q3



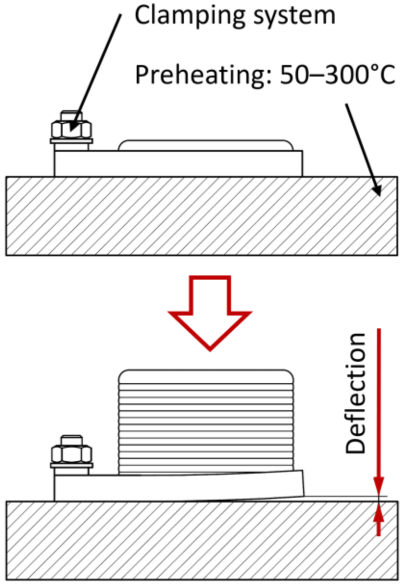
Materials and methods – Q3

Material

- Base material – AZ31
- Filler material – AZ61

Sample type

- Thin-walled sample
- Volumetric sample



Analysis

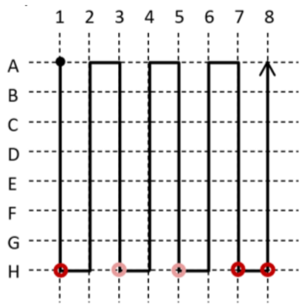
- Dimensional accuracy, grain size, microhardness
- Residual stress – indirect analysis (deflection)

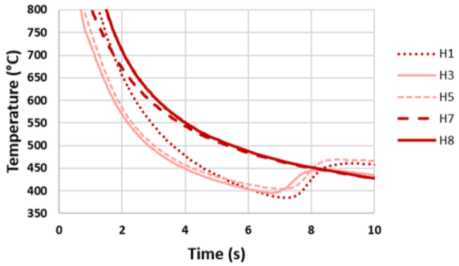
Desired output

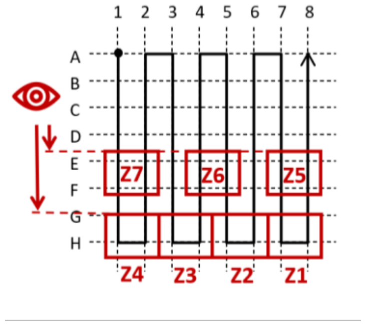
- Overheating prediction
- Height deviation, deflection
- Microstructure + mechanical properties

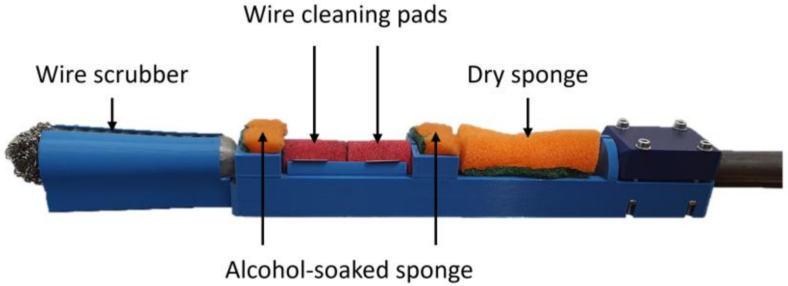
Experimental setup development

- Filler wire cleaning system II. generation







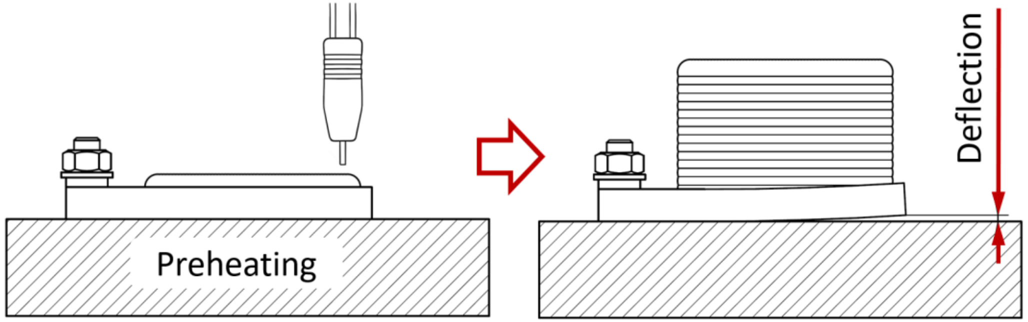


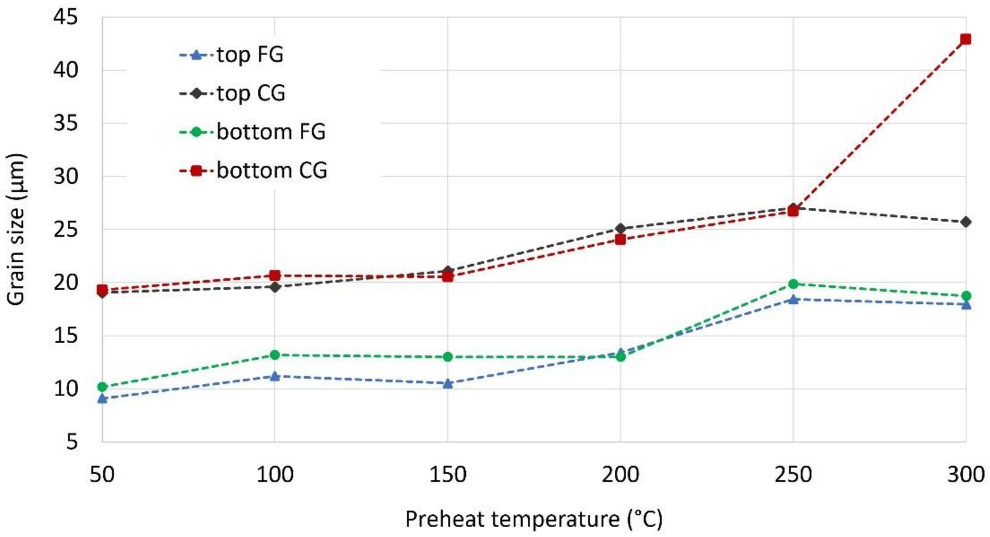
Results and Discussion

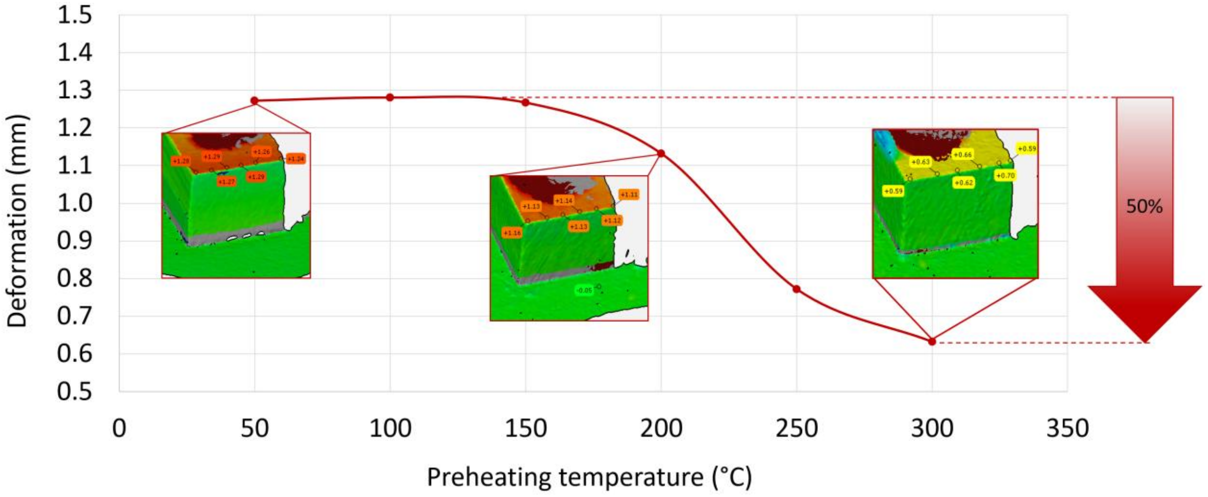
Scientific question 3 – thermal management strategies (H3)

Preheating, volumetric strategies

- Six different preheating temperatures 50–300 °C
- Higher preheating – decreasing deflection, increasing grain size
- 250 °C - deflection reduced by 40%, grain size (19.2–26.9 μm)
- This grain size remains acceptable







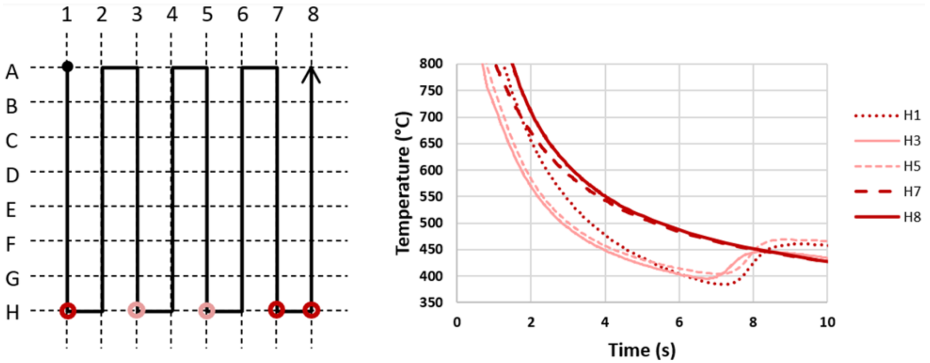
Results and Discussion

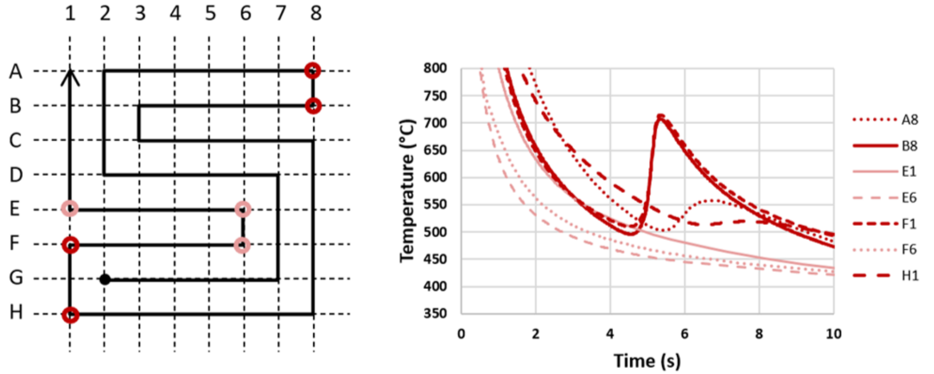
Scientific question 3 – thermal management strategies (H3)

Preheating, **volumetric strategies**

- Three different strategies - ZigZag, Spiral, S-pattern
- Thermal simulation to identify slow-cooling regions – grain coarsening
- Deflection reduced by 40%, grain size from 19.2 to 26.9 µm
- S-pattern trajectory - most uniform heat distribution
  - narrowest grain-size range (26.32–44.71 µm)
- Hall–Petch relationship – microstructure corresponds with microhardness

ZigZag		Spiral		S-pattern	
Position	Avg. size (µm)	Position	Avg. size (µm)	Position	Avg. size (µm)
E5	26,46 ±6,63	G4	34,76 ±9,47	B7	38,52 ±8,84
E8	44,36 ±13,92	G7	37,97 ±12,33	E2	30,60 ±8,87
G3	28,73 ±7,73	H4	39,75 ±13,50	F2	39,01 ±11,31
G6	38,09 ±11,61	H8	60,27 ±22,69	F5	26,32 ±7,14
G8	51,88 ±12,58			H1	44,71 ±11,63





Results and Discussion

Scientific question 3 – thermal management strategies (H3)

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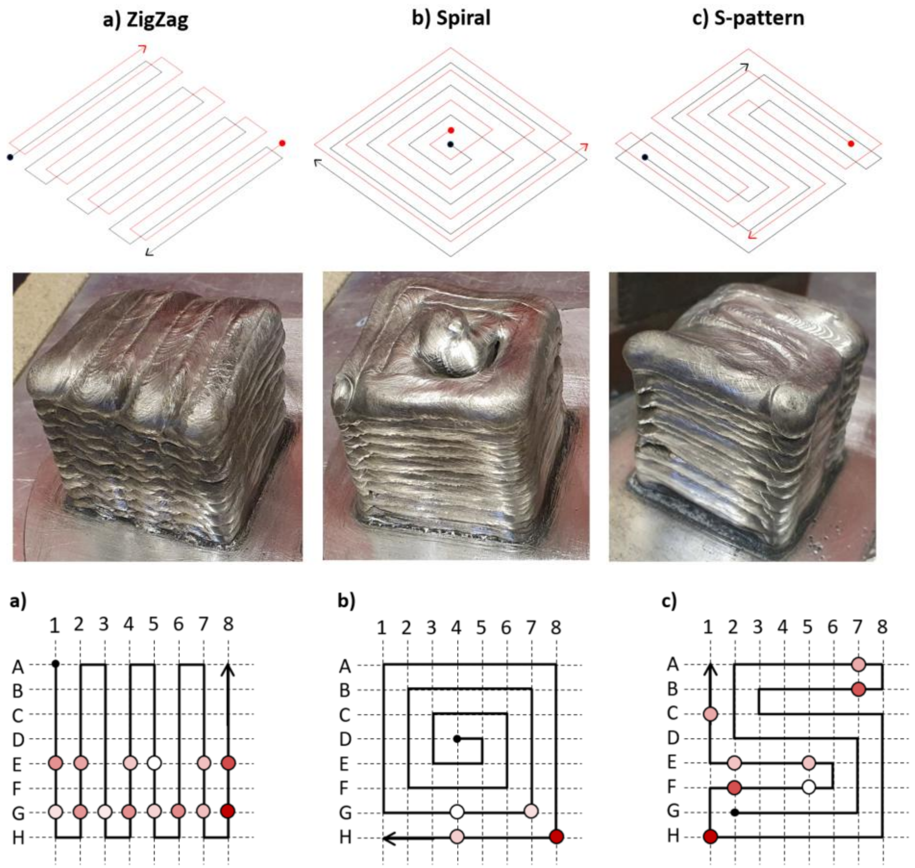


Conclusions

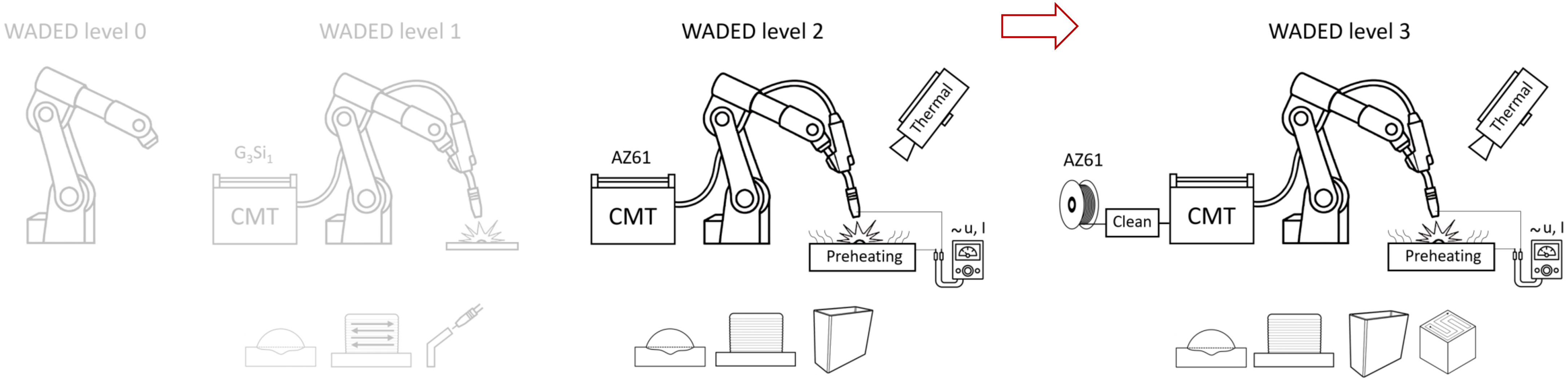
Evaluation of scientific questions

Q3: How do thermal management strategies affect the development of microstructure and residual stresses?

- Increasing preheating and interpass temperatures reduces residual stresses while promoting grain growth
- Regions with reduced cooling rates were found to promote significant grain coarsening
- More uniform heat distribution led to the lowest maximum grain size and the narrowest grain-size range

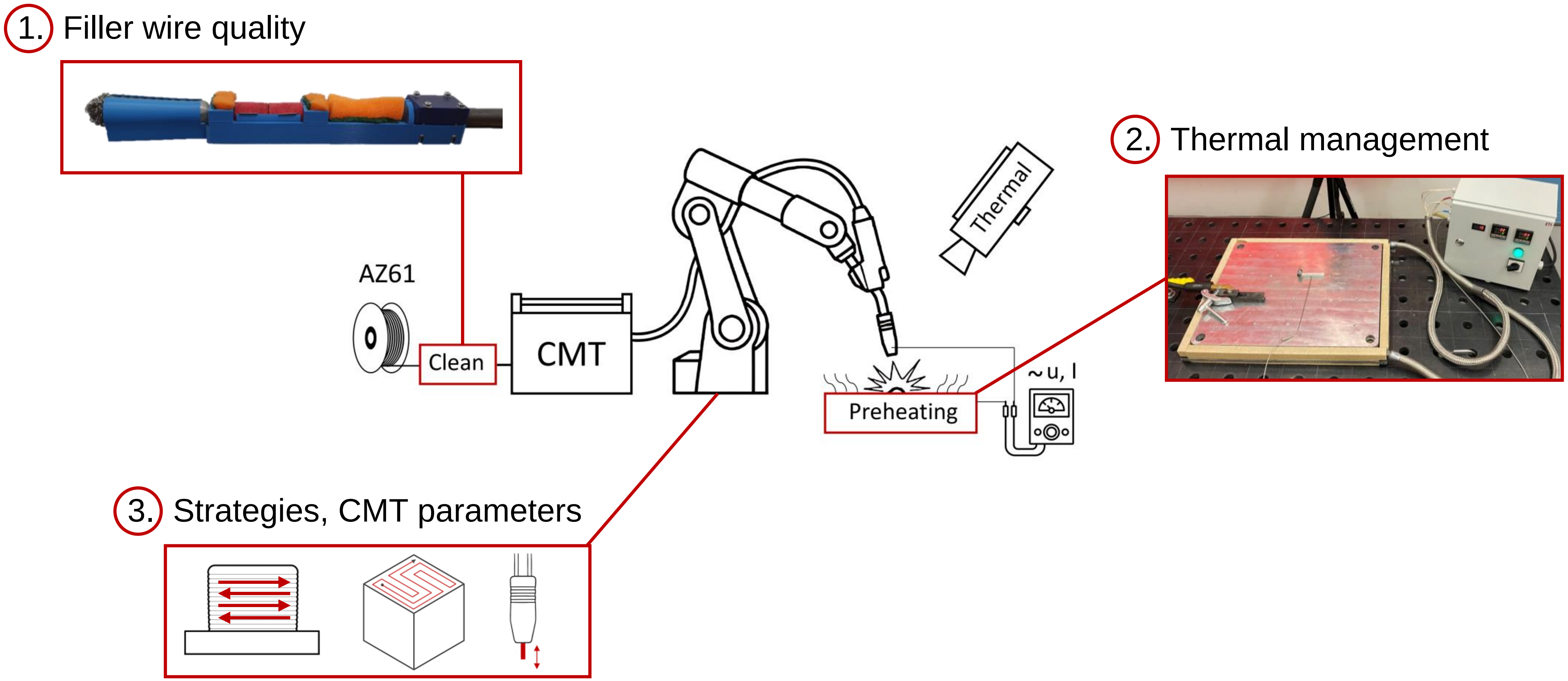
H3 hypothesis

Not falsified



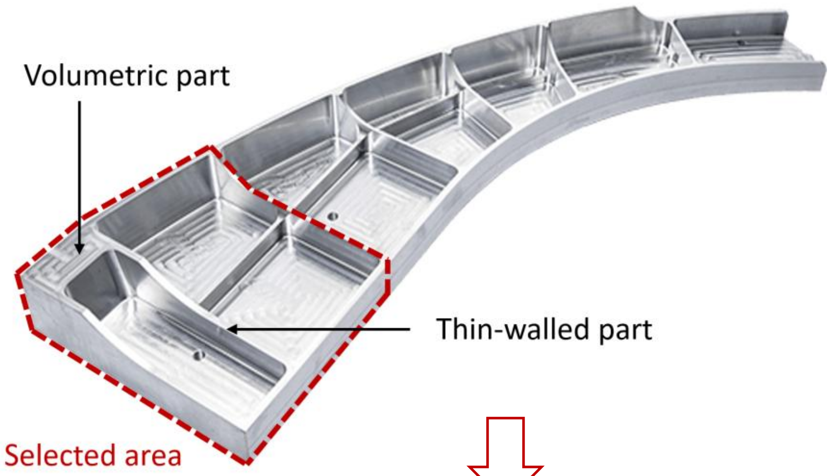
Main conclusion

Key takeaways



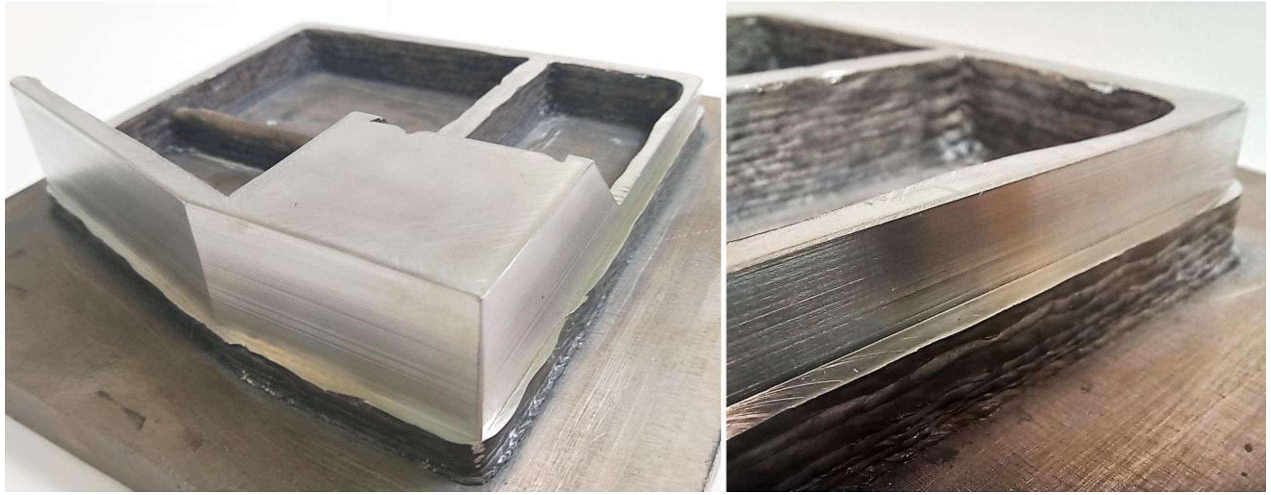
Main conclusion

Structured component demonstrator



Aircraft C-shape frame

- Improved BTF ratio: material waste ~70% → 10%
- Mechanical properties between cast and wrought alloys



Future research

- Fatigue behaviour, heat treatment, surface treatment

List of publications

Publications:

- SLAVÍČEK, J.; FRANKE, J.; JAROŠ, J.; KOUTNÝ, D. Strategies for wire arc additive manufacturing of thin walls and overhangs. Journal of Mechanical Science and Technology, 2023, vol. 37, no. 1, p. 5529-5534. ISSN: 1738-494X. Q3
- SLAVÍČEK, J.; ŠVÁB, Č.; GNEIGER, S.; HURNÍK, J.; PROCHÁZKA, P.; KOUTNÝ, D.; Wire-arc directed energy deposition of AZ61 magnesium alloy fabricated by cold metal transfer: Processing, microstructure, and mechanical properties, Scientific Reports, 2026, p. 1-22, ISSN 2045-2322. Q1
- SLAVÍČEK, J.; ZEMAN, S.; HORYNOVÁ, M.; SENCK, S.; KOUTNÝ, D.; Optimisation of preheating and interpass temperature in WADED magnesium alloy AZ61: A comparative study on microstructure, residual stresses, and internal defects, Journal of Advanced Joining Processes, 2026, vol. 13, p. 1-15, ISSN: 2666-3309 Q1
- SEIDLER, F.; SLAVÍČEK, J.; KOUTNÝ, D.; Influence of deposition strategy on the microstructure of volumetric WADED-fabricated AZ61 magnesium alloy components, Additive manufacturing letters, 2025, vol. 16, p. 1-10, ISSN: 2772-3690 Q2

Conferences:

- SLAVÍČEK, J.; ŠVÁB, Č.; ZEMAN, S.; SEIDLER, F.; HORYNOVÁ, M.; GNEIGER, S.; SENCK, S.; KOUTNÝ, D. Process development for complex magnesium parts produced by WADED, WAMS26, 8.–11.6.2026, ESA-ESTEC, Noordwijk, The Netherlands
- SLAVÍČEK, J.; HURNÍK, J.; KOUTNÝ, D. Strategy for wire arc additive manufacturing of thin walls. Reliability and Design of Additively Manufactured Materials, 4.–6.10. 2022, Belgrade, Serbia.

THANK YOU FOR YOUR ATTENTION

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