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Influence of the preheating on the microstructure evolution within thick deposits of AISI M4 high speed steel processed by Laser-Directed Energy Deposition, based on thermal modelling, hardness characterization, and dilatometry tests

J. Tchoufang Tchuindjang, O. Dedry, R. Carrus, R. T. Jardin, V. Tuninetti, A. M. Habraken and A.I.M. Mertens

Outline

- Background (issues about additive manufacturing on tool steels, especially residual stresses and cracks + microstructure variation within thick deposits (see Hashemi et al. (2017), with properties influenced by microstructure features, including grain sizes and nature/distribution of the phases)
- Materials and Methods (including the three studied configurations (Thick 3D for improved wear properties under delayed preheating, Large 3D with direct inductive preheating, 2D with laser preheating for thermomechanical modeling, and final Thick 3D with inductive preheating + varying processing parameters to achieve homogeneous microstructure)
- Results (3D block with heterogeneous microstructure within the height (Jardin et al. (2019) and 2D thermal model; 2D thin wall for thermomechanical model and laser preheating with enhancement of microstructure evolution during processing (show restored thermal histories within 1st, 5th and 10th layer and assumption of desaturation with heat accumulation, except for the last layer + assumption of homogeneous microstructure for almost all the height of the thin wall (Jardin et al. (2021); 3D Blocks under varying processing parameters (achievement of melt pool of constant sizes to lead to homogeneous microstructure within the height of the thick deposit, the optimized parameters also helping to achieve a stress and crack-free deposit)
- Conclusions and perspectives

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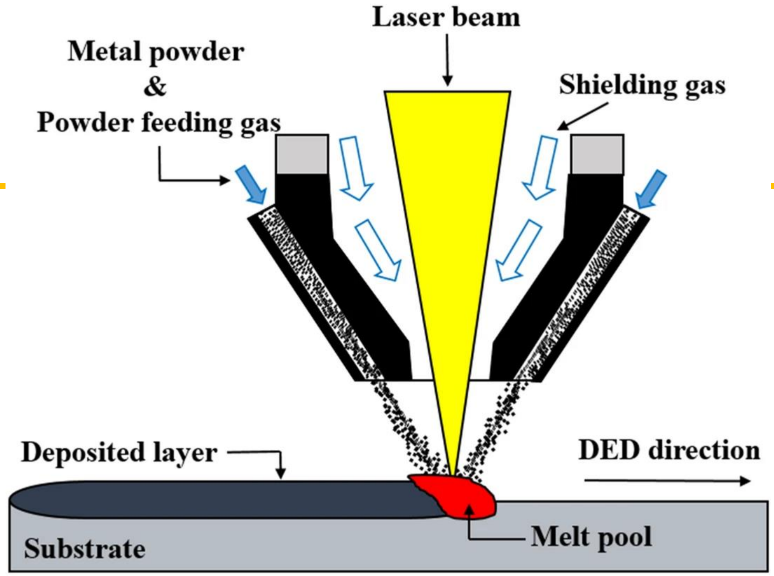
Background…

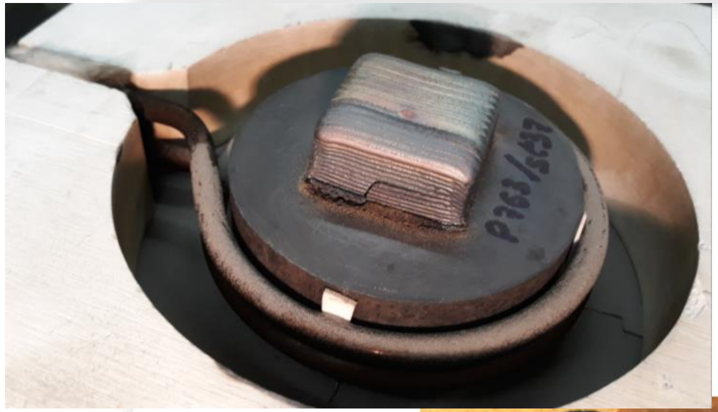
- AISI High Speed Steel (HSS) M4 belonging to the complex fe-Cr-C-X system, X being a strong carbide forming element (i.e. V, Mo, W, Nb, etc.)
- Hard carbides to increase hardness and improve wear resistance, associated with a tempered martensite to achieve strength and toughness
- Applications : tool steels, die castings, rolls, etc.
- M4 with AM (DED) for repairing purpose, hard coatings, etc. [3]

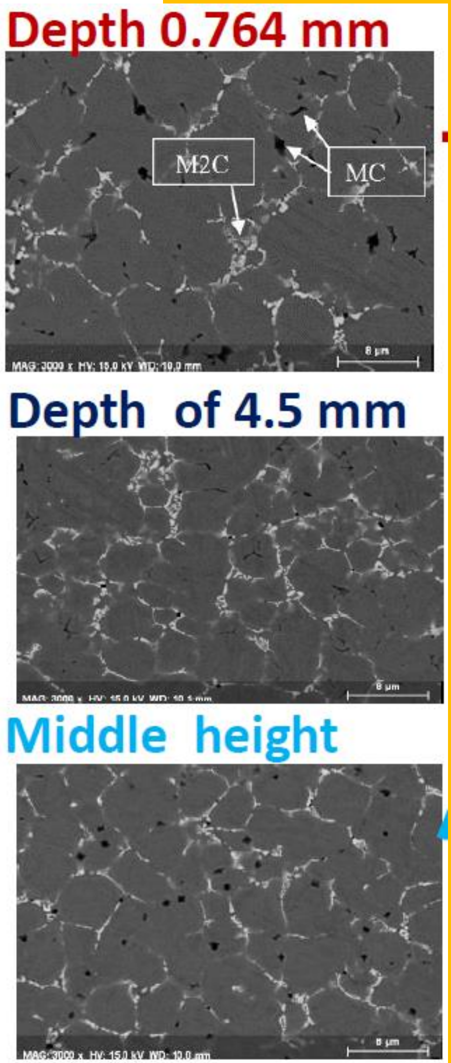
[1] J-S lim et al., Sci. Rep. 11 (2021)
[2] Jardin et al., Metals 10 (2020)
[3] Jardin, Tchoufang Tchuindjang et al., Mat. Let. 236 (2019)

Background…



- DED process [1]
- Cracks and residual stresses when processing Tool Steels under DED [2]
- Heterogeneous microstructures for thicker deposits [3]





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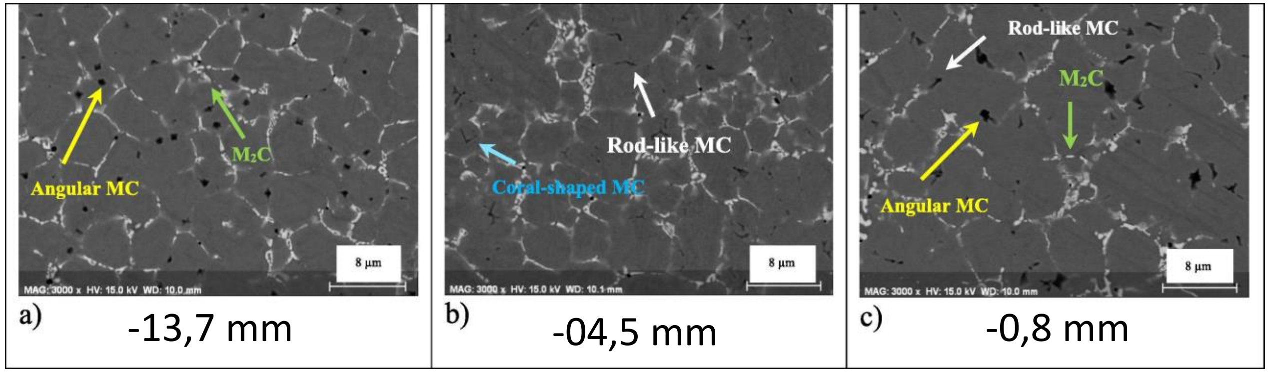
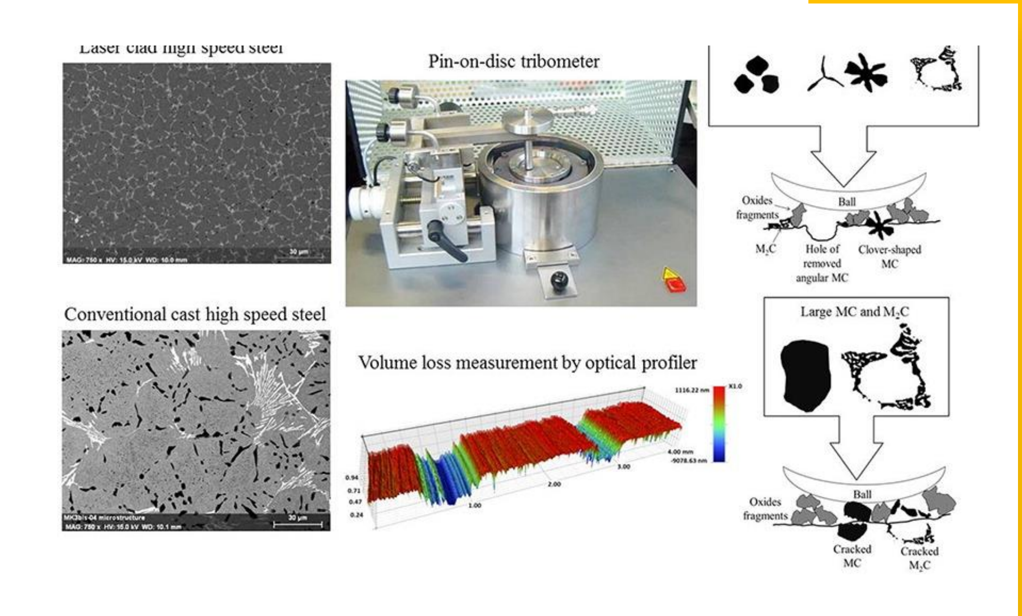
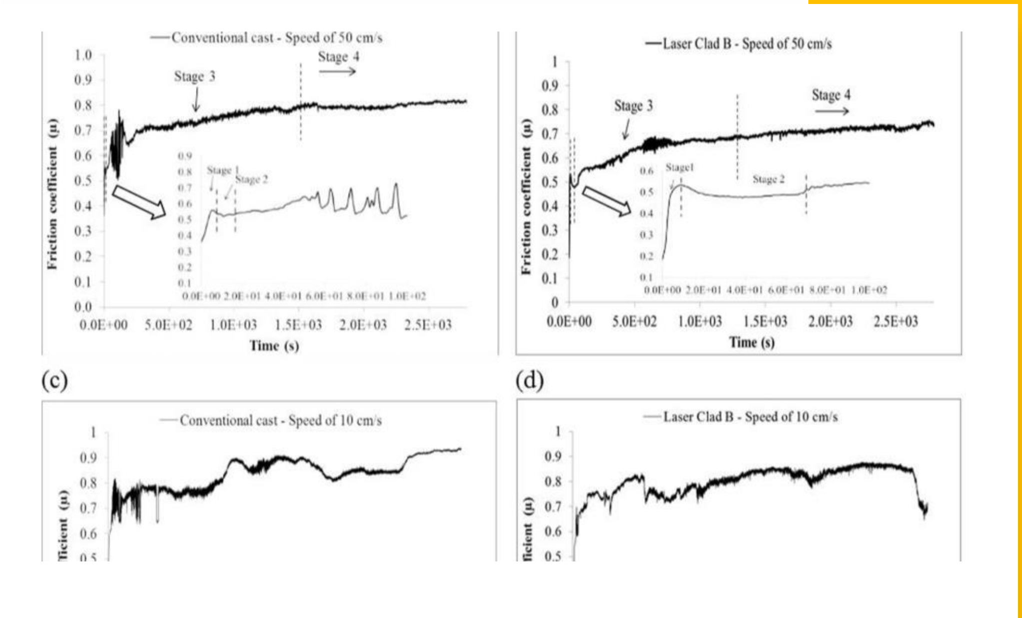
Background

- Significant decrease of both the grain size and the carbides from DED compared to conventional casting [1]
- Improvement of mechanical behavior especially wear resistance [1]
- Heterogeneities regarding the microstructure (within the height of the deposit) [2]







[1] Hashemi, Mertens et al., S&CT 315 (2017)
[2] Jardin, Tchoufang Tchuindjang et al., Mat. Let. 236 (2019)

Materials and Methods

- HSS AISI M4 powder as raw material from preliminary campaign results
- 3 processing routes…
- Samples shape and sizes adapted to final goals (mechanical properties, Modeling, etc.)
- Various techniques to achieve both macro and microstructure study and characterization (SEM-EDS/EBSD, XRD, Macro ad Nano hardness, pin-on-disk, etc.)
- 2D and 3D FEA simulations to set validated thermal models and one thermomechanical model
- Switching from constant to varying processing parameters to achieve the final goal : **homogeneous microstructure within a crack-free thick deposit**

[1] Hashemi, Mertens et al., S&CT 315 (2017)
[2] Jardin, Tchoufang Tchuindjang et al., Mat. Let. 236 (2019)

Materials and Methods

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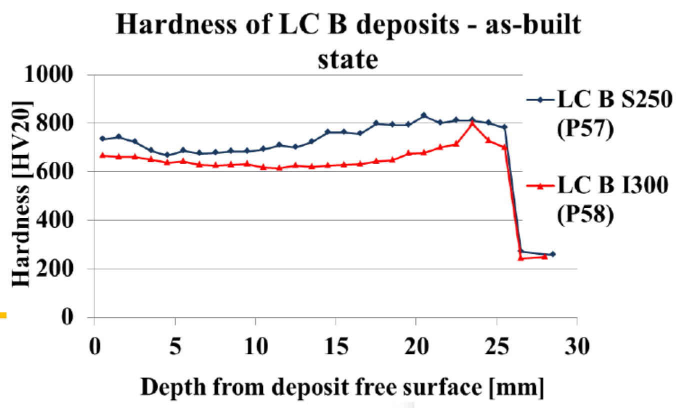
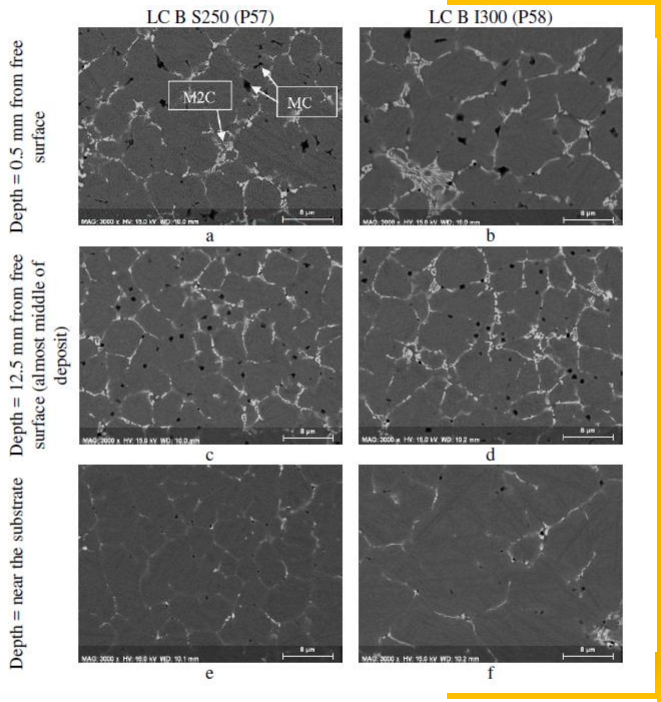
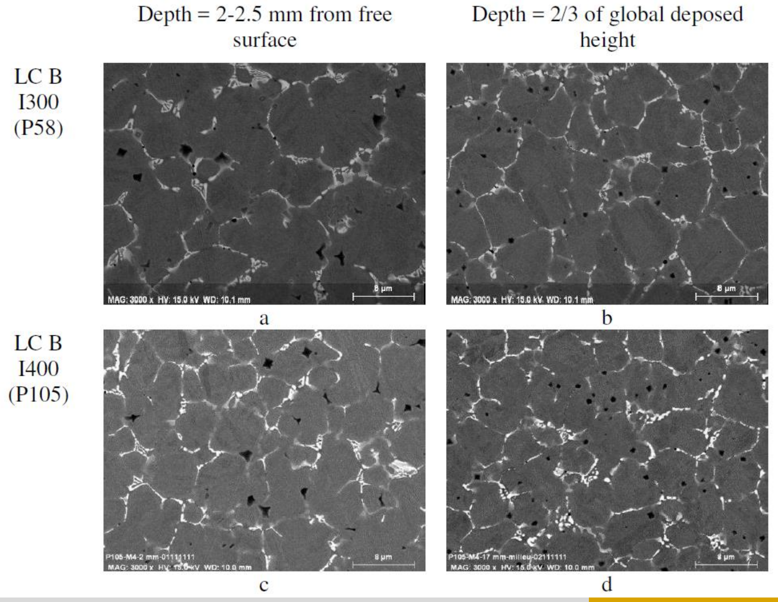
Results (3D Bulk – Microstructure Heterogeneity and 2D Thermal modeling)







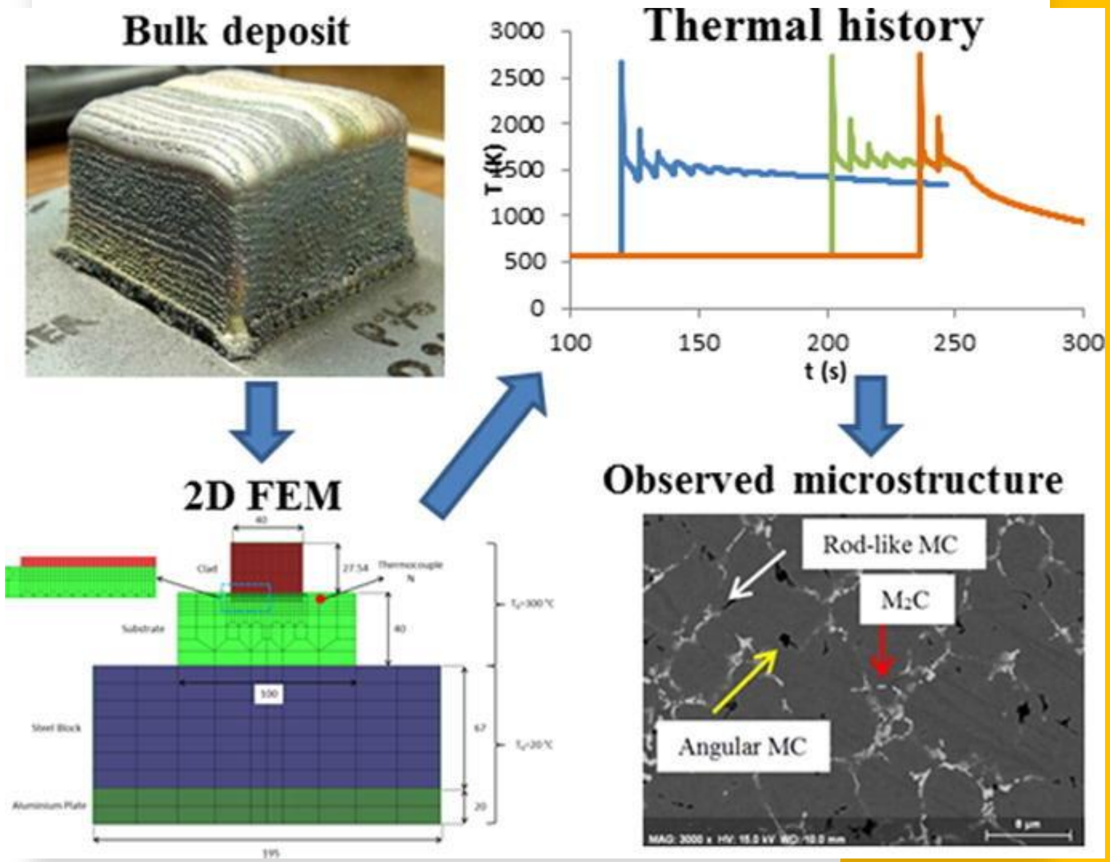
- Cellular-type structure with grain size changing from the surface to the bonding with the substrate [1]
- Microstructure changes depending on the preheating temperature (250 °C vs 300°C), higher preheating leading to larger grain size [1]
- Carbides distribution changing within the height of the deposit [1, 2]
- Hardness profile changing depending on the processing parameters, including preheating T°

[1] Hashemi, PhD Thesis (ULiège, 2017)
[2] Jardin, Tchoufang Tchuindjang et al., Mat. Let. 236 (2019)

Results (3D Bulk – Microstructure Heterogeneity and 2D Thermal modeling)

- Preheating @ 300°C via induction mode
- Crack-free 3D bulk sample (40X40Xh27.5)
- 42CrMo4 substrate
- 2D FEA under LAGAMINE® code using Element birth technique with measured thermophysical parameters
- Sensitivity analysis of MP size and recorded (within the substrate)
- thermal history performed on MP tructure changes depending on the preheating temperature (250 °C vs 300°C), higher preheating leading to larger grain size [1]

	Bulk Sample
Laser beam speed (mm/s)	6.67
Laser power (W)	1100
Pre-heating (°C)	300
Mass flow (mg/s)	76
Number of tracks per layer	27
Total number of layers	36



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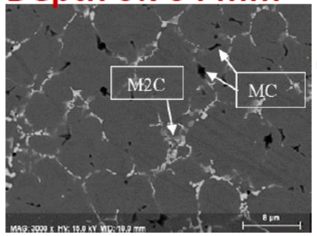
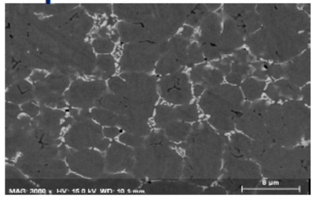
Results (3D Bulk sample – Microstructure Heterogeneity and 2D Thermal modeling)

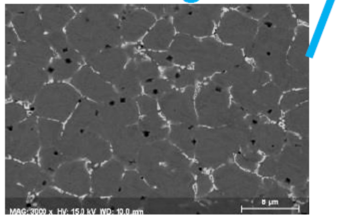
Depth 0.764 mm



Depth of 4.5 mm



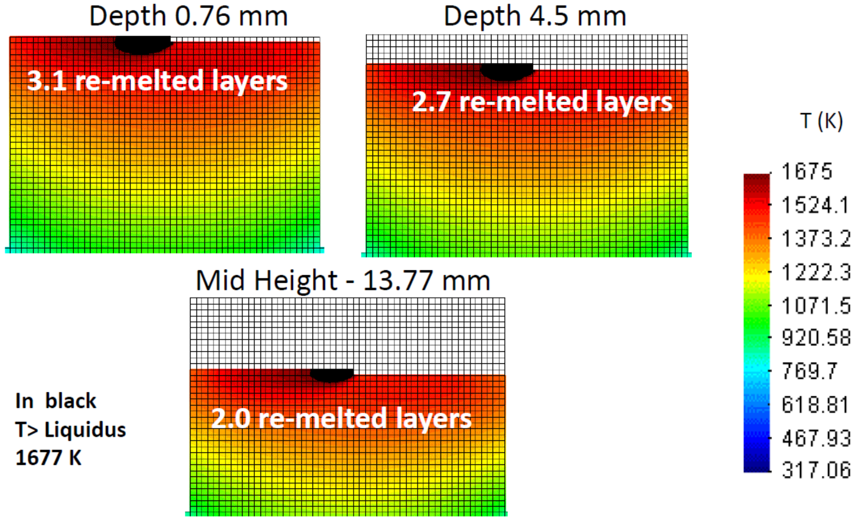
Middle height

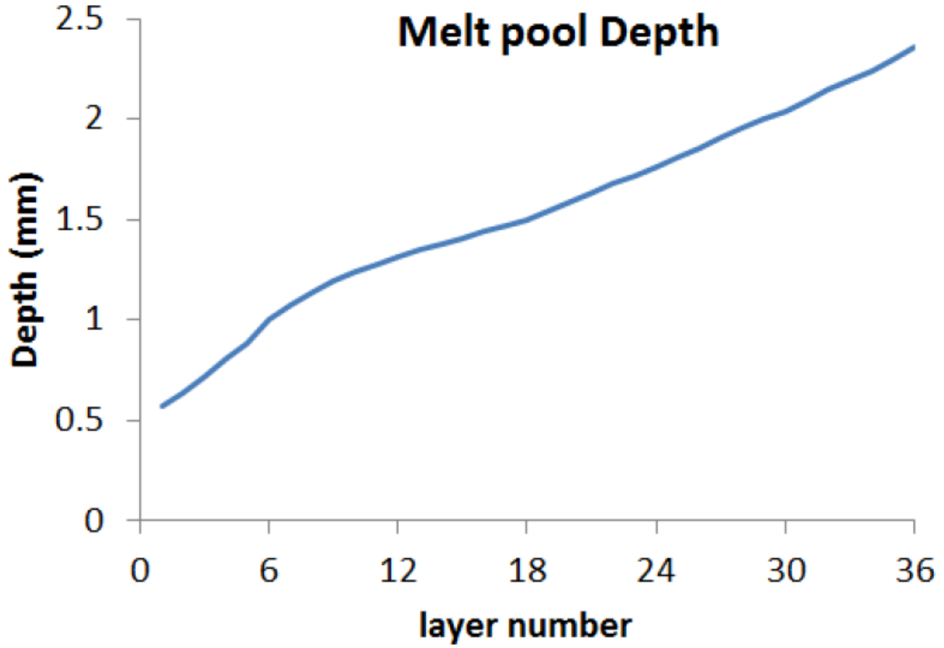


Clover-like MC carbides in intercellular zones formed after the primary cells (high superheating temperature) + coarsening

Lower superheating temperature
Higher number of partial remeltings
→ coral like MC carbides inside cells formed in the first solid matrix + growth process

For all locations similar cooling end
Precipitation of eutectic M_2C carbides





Heat accumulation during processing + constant processing parameters → Change within the MP → Variation within the microstructure (grain size, shape/distribution/size of carbides size [1]

[1] Jardin, Tchoufang Tchuindjang et al., Mat. Let. 236 (2019)

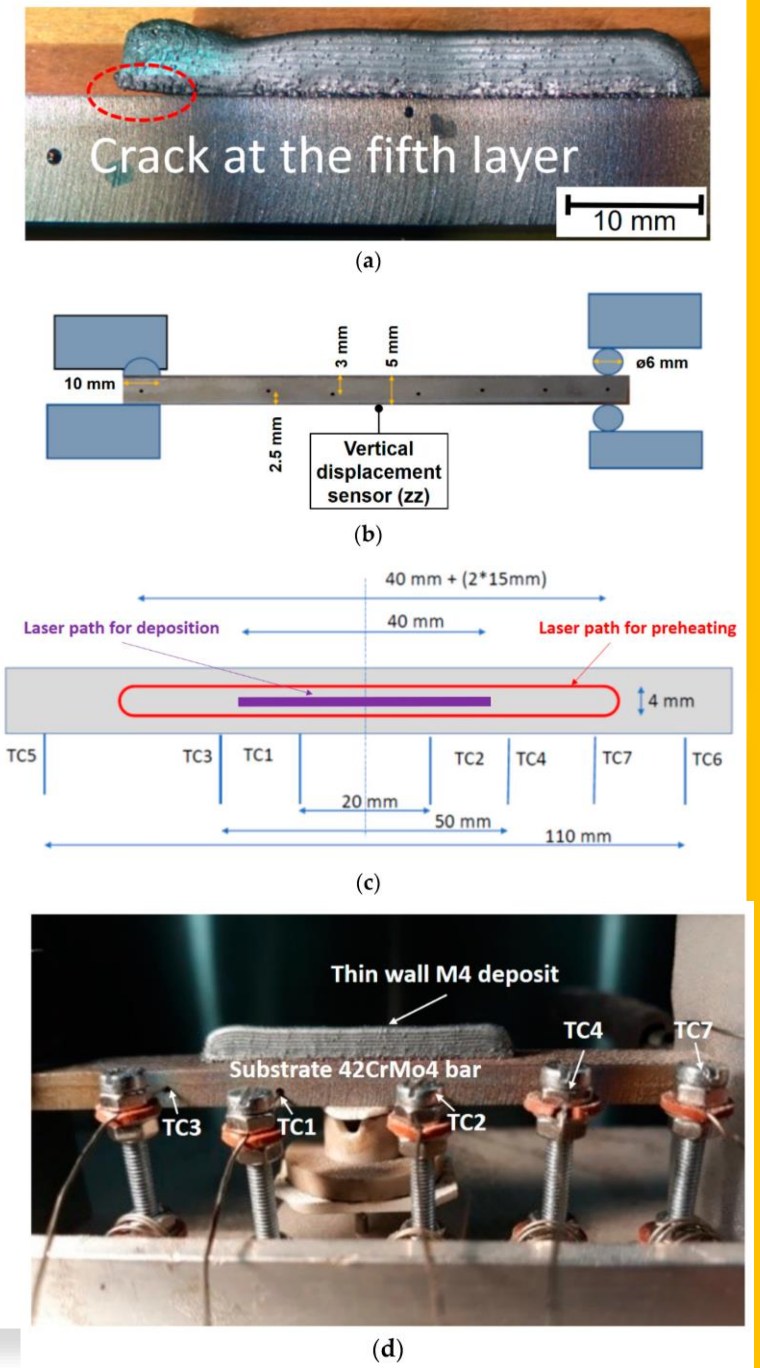
Results (2D Thin wall and 3D Thermal Modeling + Thermomechanical model)

- 42crMo4 substrate (plate), with an adequate thickness (stiffness and bending !)
- Laser as preheating source for the substrate
- Need for decreasing the laser power during deposition
- Simulation and sensitivity analysis up to the 5th layer (over 10)

	Laser Pass Length for Pre-Heating and Cladding (mm)	Laser Beam Speed (mm/s)	Laser Power (W)	Temperature at TC2 at the End of Pre-Heating and at Beginning of Cladding (°C)	Number of Laser Passes
Substrate pre-heating 1	40	41.7	260	217	20
Clad deposition 1	40	8.3	500	134	10
Substrate pre-heating 2	70	41.7	260	400	20
Clad deposition 2	40	8.3	600–400 [1]	310	10

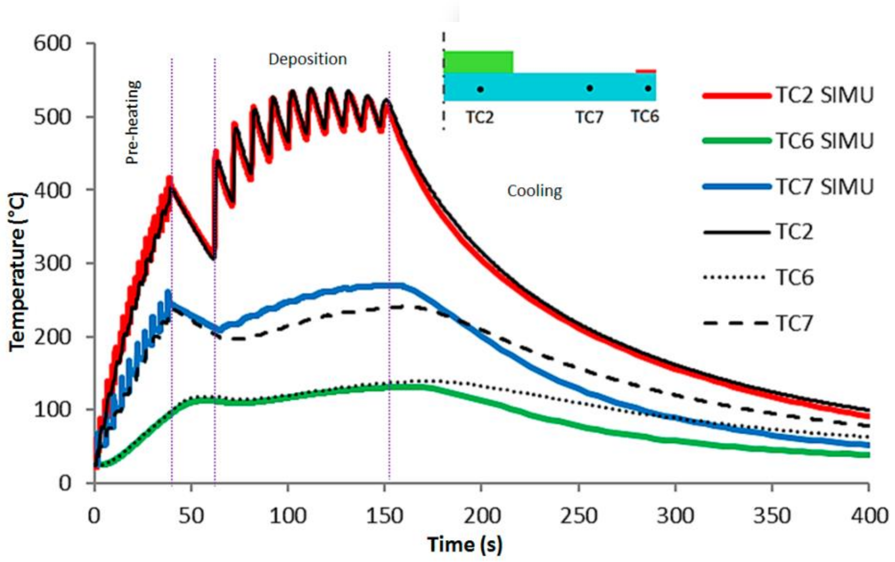
[1] The power decreased linearly with the number of layers from 600 W for the first layer to 400 W at the end of the clad.

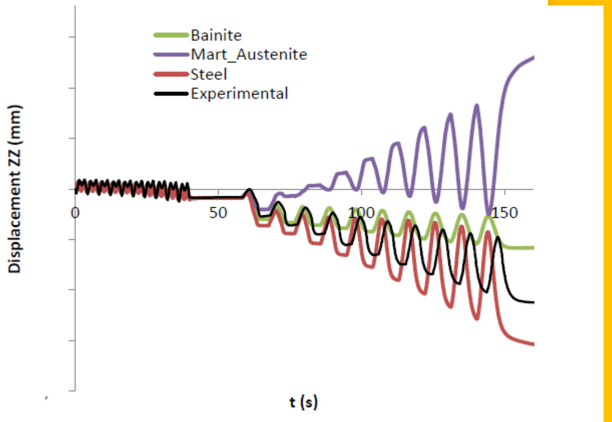
[1] Jardin et al. Metals 10(2020)

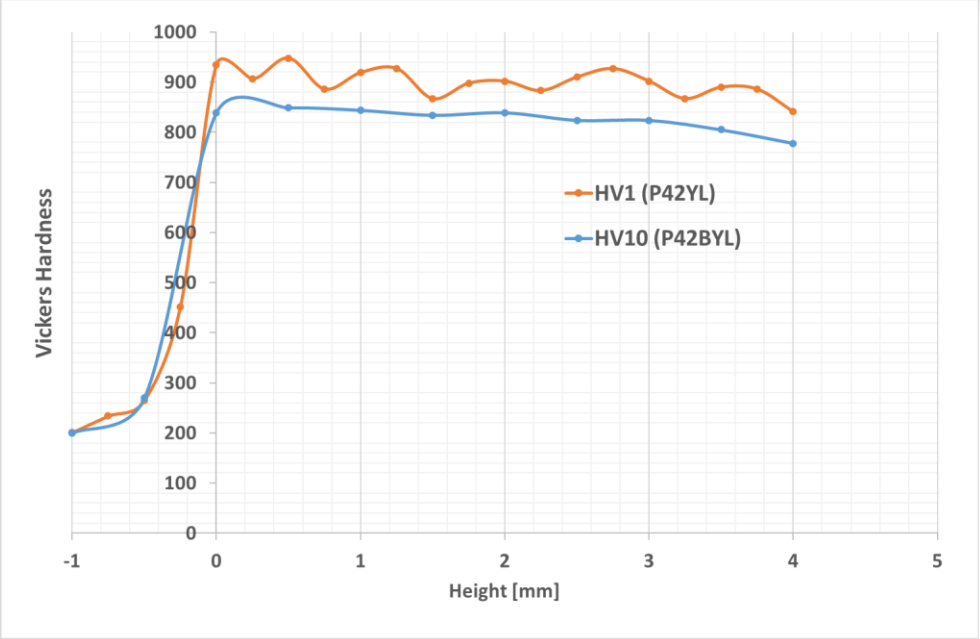


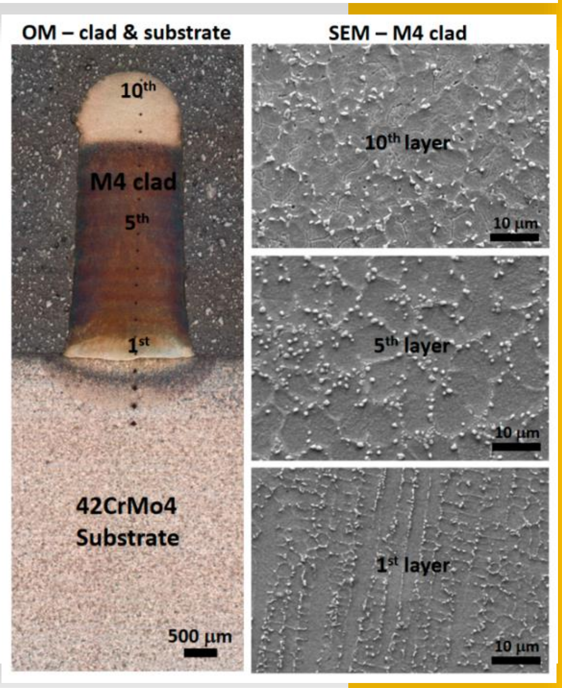
Results (2D Thin wall and 3D Thermal Modeling + Thermomechanical model)

- Validation of numerical results with thermal histories based on recorded temperature within the substrate
- Strong sensitivity to the dilatation coefficient of the clad (based on single phase assumption)
- Hardness profile (Macro HV10) following a linear decreasing trend with the height of the deposit
- Micro hardness (HV1) profile influenced by ZAT and MP for intermediate layers







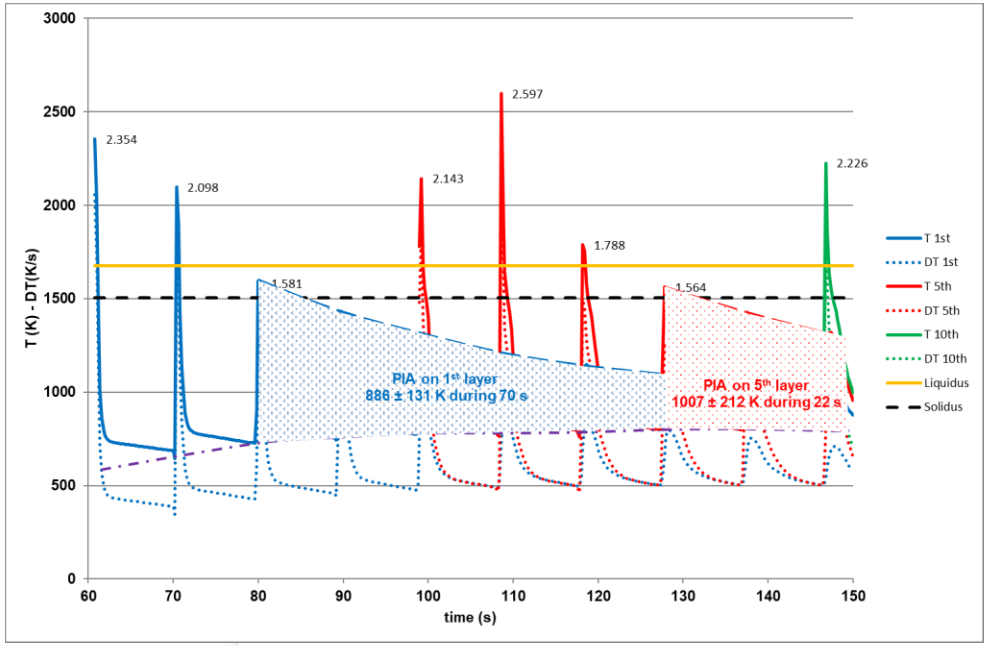


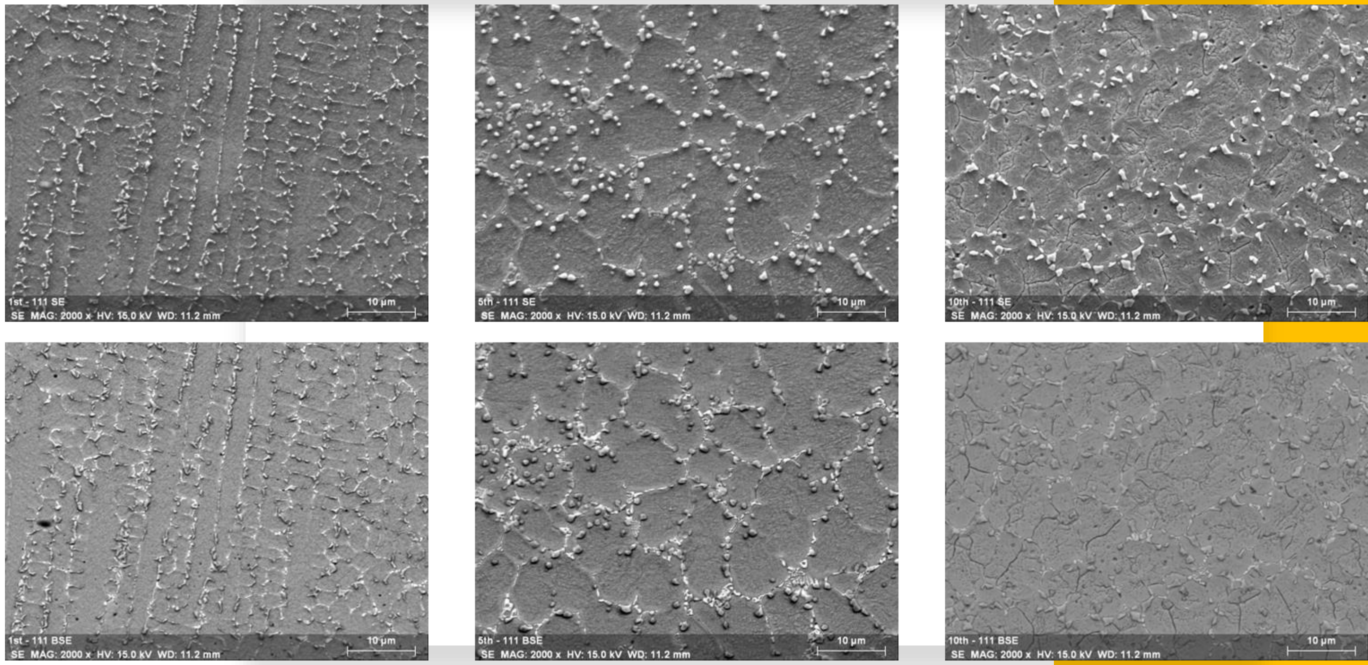
[1] Jardin et al. Metals 10(2020)

Results (2D Thin wall and 3D Thermal Modeling + Thermomechanical model)

- Super heating decreases from 1st (595K) to 5th (285K) layer before increasing again on 10th layer (723K, no remelting)).
- Cooling rate during the last solidification stage at 1610K/s, 448 K/s and 864 K/s, for 1st, 5th and 10th layer respectively → **correlation with cell/SDAS size.**
- Macrostructure: changes from Columnar dendritic mode (1st layer) to cellular mode (5th and 10th layers)
- Microstructure made of martensite type 2 (from under saturated austenite (after secondary precipitation during PIA) within layer 2 to 9, and martensite type 1 with supersaturated retained austenite (layer 10, no secondary precipitation)
- Assumption of martensite formation (type 1 and type 2) during the final cooling stage (when the laser beam is switched off)

[1] Jardin et al. Metals 10(2020)

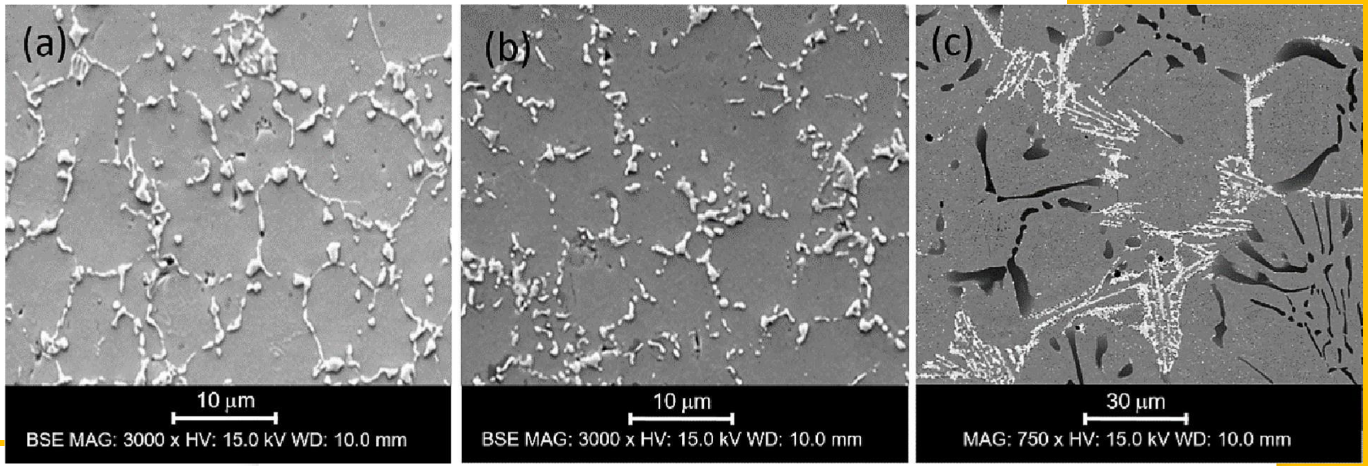




1st layer SE/BSE **5th layer SE/BSE** **10th layer SE/BSE**

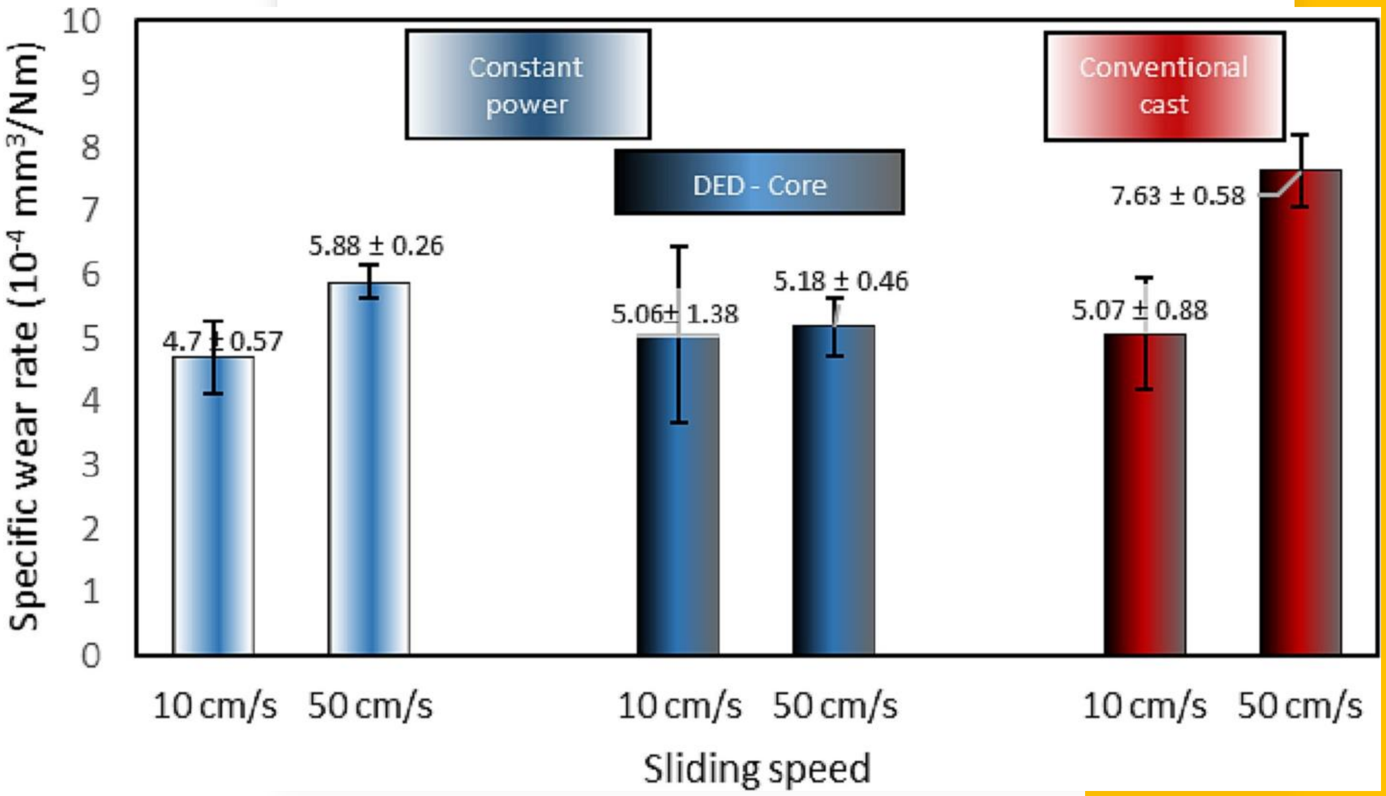
Results (3D Bulk and thick samples with varying processing parameters to achieve a homogeneous microstructure)

- Improved wear resistance for DEDed HSS M4 compared to conventional HSS due to both macrostructure and microstructural features
- Microstructure heterogeneity within a thick HSS M4 deposit influences mechanical properties and tribological behavior.
- Microstructure heterogeneity under DED as the result of varying thermal histories within the thick deposit, especially the MP size
- What about changing from constant processing parameters to varying ones to achieved constant MP?



Fine cellular microstructure in HSS M4 bulk deposits under constant processing parameters : (a) near the surface, (b) within the mid height

Coarse microstructure of a conventional cast HSS sample



[1] Jardin et al. Optics and Laser Tech, etals 10(2020)

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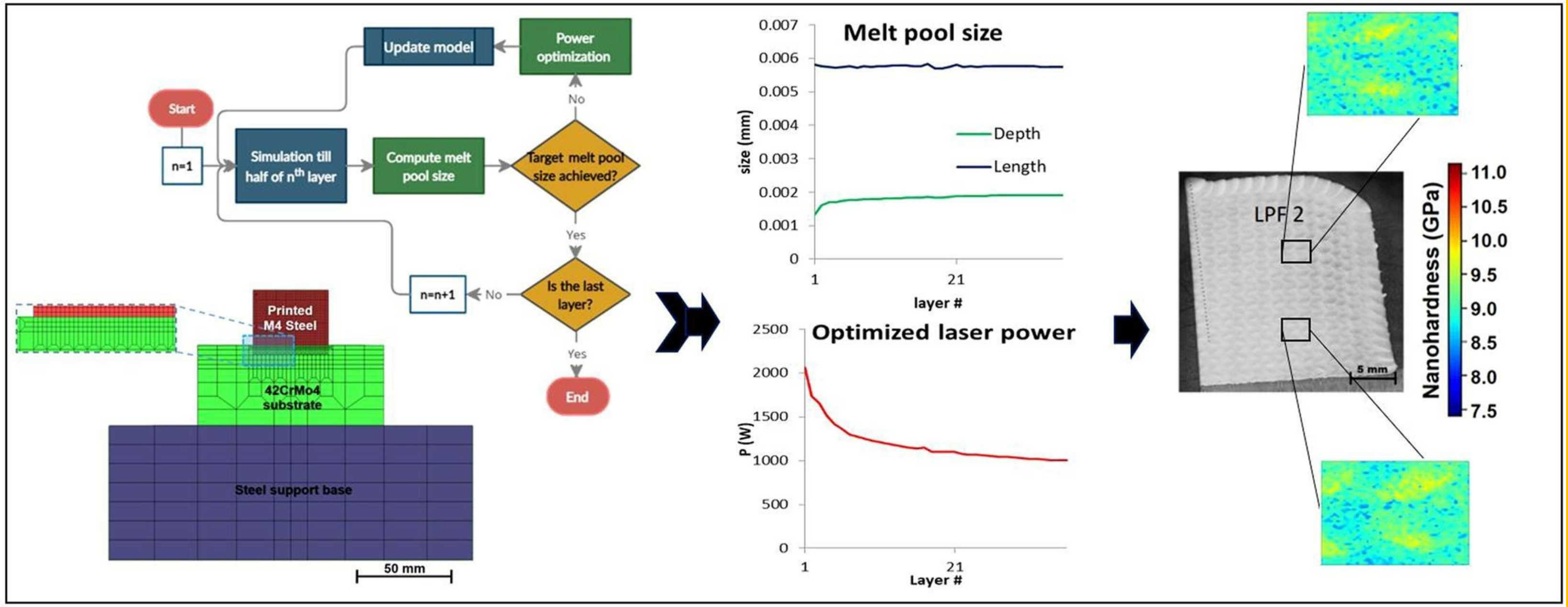
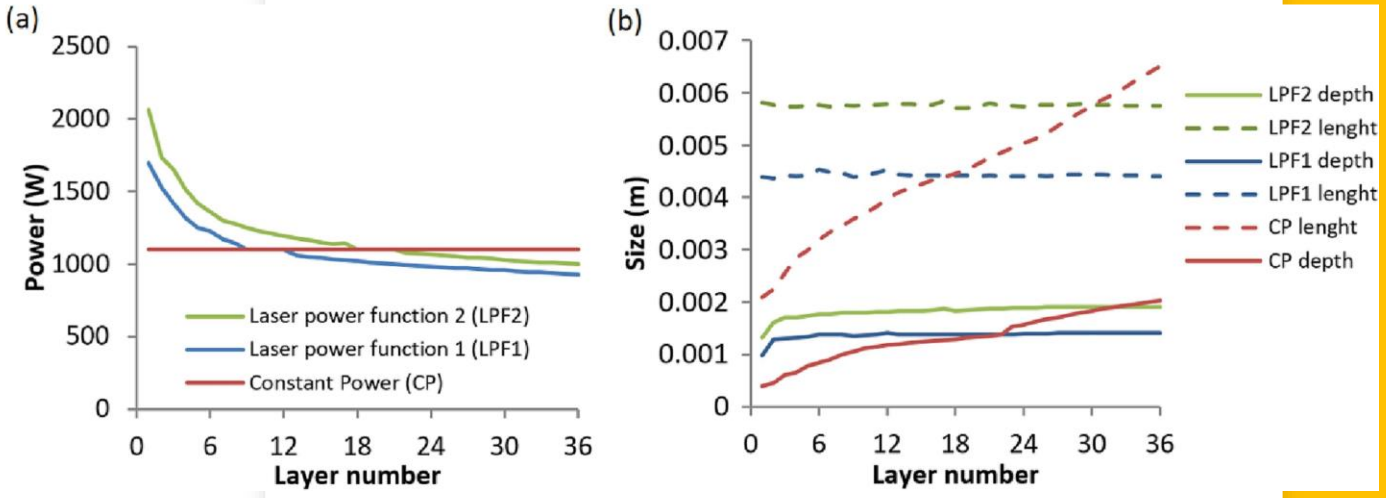


- 3 DEDed thick deposits, one with constant processing parameters (CP), and two with varying parameters (laser power function LFP1 and LFP2.
- LFP designed to achieved a MP with defined size (depth and length) based on updated iteration of the validated thermal model
- Microstructure homogeneity assessed form hardness profile (Macrostructure) and Nano hardness map (microstructure)

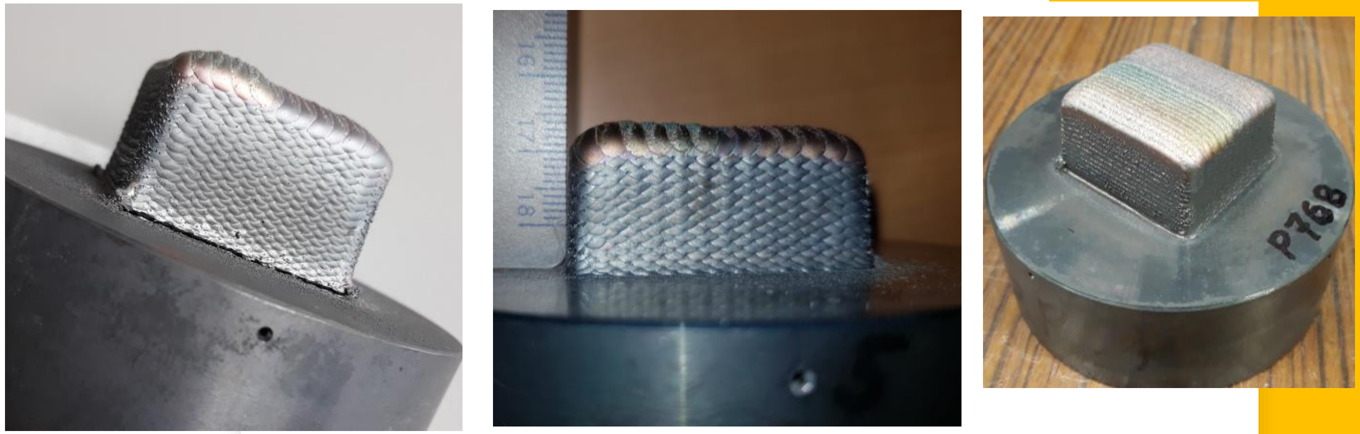


(a) Laser power functions obtained from the proposed methodology
(b) Computed molten pool over the layers for LPF1, LPF2 and CP.

[1] Jardin et al. Optics and Laser Tech, etals 10(2020)

Results (3D Bulk and thick samples with varying processing parameters to achieve a homogeneous microstructure)

- Processing parameters for CP, and LFPs configurations
- As-built samples without cracks



Cuboid parts	Total height (Z direction, mm)	Width (X direction, mm)	Length (Y direction mm)	Vickers Hardness profile length	Position of Vickers Hardness profile within deposit	
					X (mm)	Y (mm)
Constant power (CP)	27.3	41.5	42	15.5	17.6	21.5
Function 1 (LPF1)	20.8	41.9	43.4	20.5	22.4	22.1
Function 2 (LPF2)	23.6	41.6	43.1	20.5	20.8	19.2

(a) Laser power functions obtained from the proposed methodology
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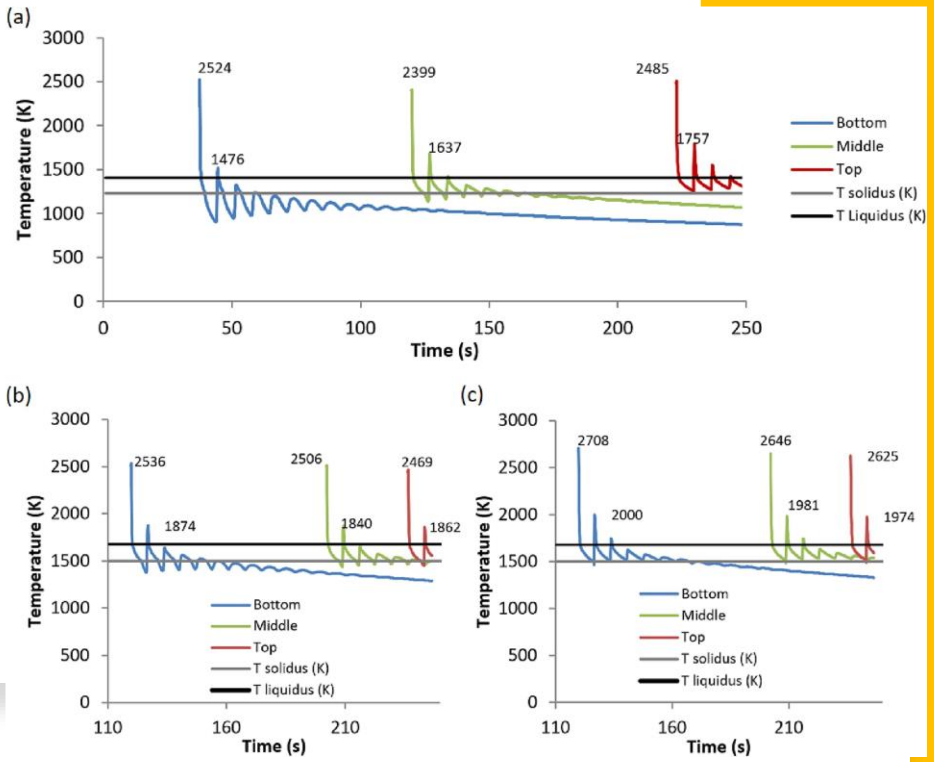
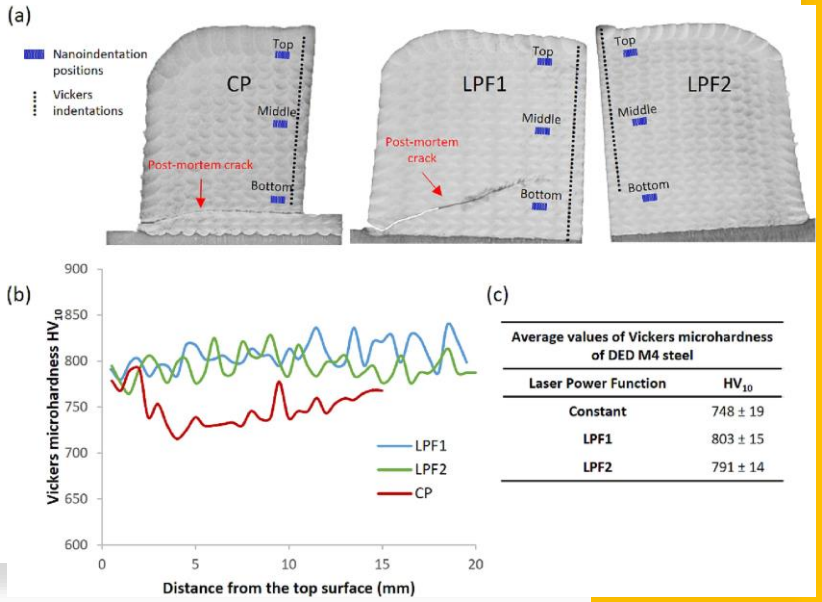
[1] Jardin et al. Optics and Laser Tech, etals 10(2020)

Results (3D Bulk and thick samples with varying processing parameters to achieve a homogeneous microstructure)

- Restored thermal histories from the thermal model for each configuration (CP, LFP1 and LFP2) showing consistency for LFP configurations according to peak temperatures, remelting sequence per layer, and average cooling trend
- Macro Hardness higher for LFPs than CP, and close to a steady state profile for LFPs compared to CP
- Cracks within CP and LFP1 configuration





Average values of Vickers microhardness of DED M4 steel

Laser Power Function	HV_{10}
Constant	748 ± 19
LPF1	803 ± 15
LPF2	791 ± 14

[1] Jardin et al. Optics and Laser Tech, etals 10(2020)

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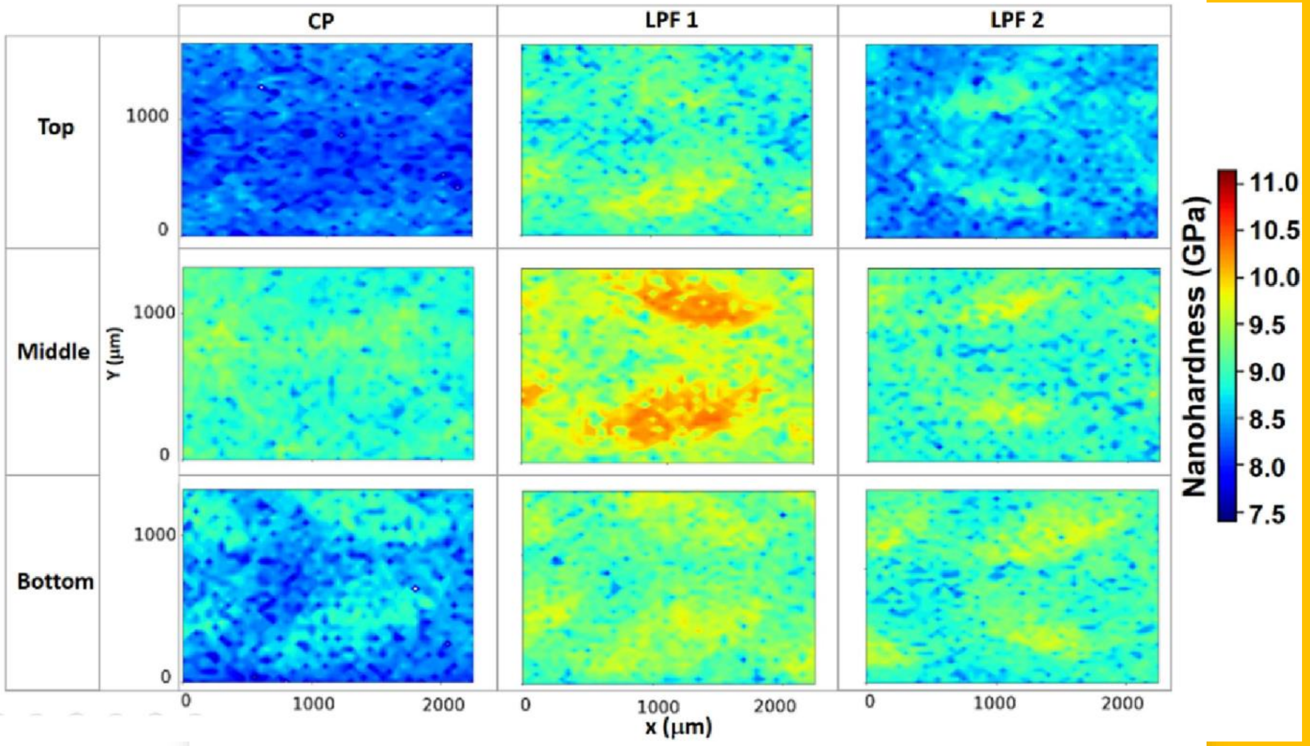

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