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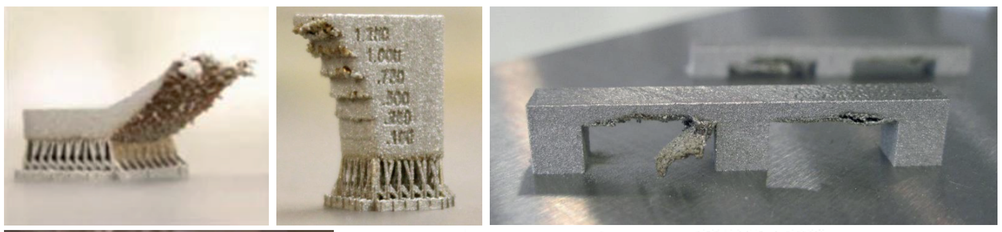
Multi-Objective Optimisation of Metal Support Structures for Laser Powder Bed Fusion Systems

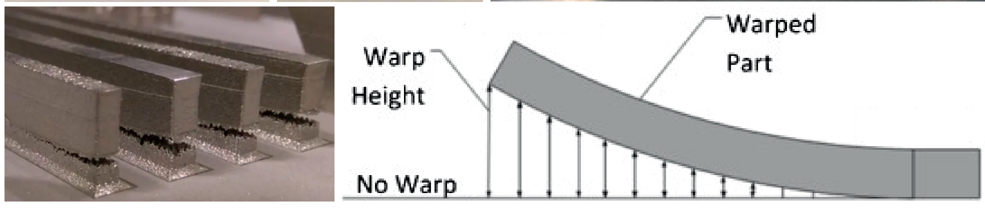
Antonios Dimopoulos

"This publication was made possible by the sponsorship and support of Lloyd's Register Foundation. The work was enabled through, and undertaken at, the National Structural Integrity Research Centre (NSIRC), a postgraduate engineering facility for industry-led research into structural integrity established and managed by TWI through a network of both national and international Universities"

Problem Statement

Laser Powder Bed Fusion (LPBF) is a rapidly developing Additive Manufacturing (AM) technology, capable of producing complex, thin, and lightweight components, which are essential properties for industries like space, healthcare, and automotive. However, because of the nature of 3D printing to build the part layer-by-layer, LPBF faces difficulties with regard to the construction of overhang structures, and the warping deformation caused by thermal stresses. Thus, support structures are always required.





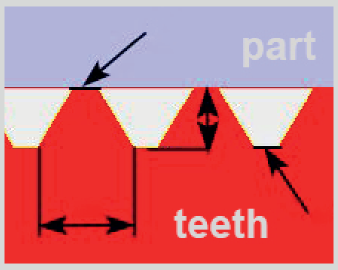
But, the addition of unnecessary supports increases the post-processing, the time and effort needed to remove the supports, the risk to damage the part, the printing time, and the amount of material.

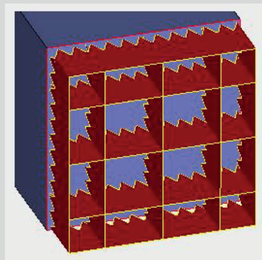
Objective & Approach

The aim of this research is to propose optimised support structures for metal AM and LPBF systems that are easy to remove reducing the time and effort needed during post-processing, and consume the minimum support material without affecting the quality of the final part. In addition, Multi-Objective Optimisation will be performed to find out the optimal parameters that minimise the Support Removal Time, Support Volume, and Warping Deformation (outputs).

Three areas of investigation (inputs)

Teeth Area | Infill Density | Laser Parameters





Simple Example of Multi-Objective Optimisation

Min $f(X_1, X_2, \ldots, X_n)$, $g(Y_1, Y_2, \ldots, Y_n)$ and $min < W < max$

Where f, g functions of removal time and support volume, X, Y independent parameters, W the warp approved area

Methodology

To be able to achieve and evaluate the aforementioned approach, different rounds of printings will be performed. During the first round, "Block" type supports will be investigated and various support structures will be generated by using small specimens composed of 0 to 45 degrees overhangs. Response Surface Methodology (RSM), based on Central Composite Design (CCD) will be also performed to define the total number of optimal specimen configurations that will be printed and tested.

6 parameters will be investigated consisted of 3 levels each

Parameter	Level 1	Level 2	Level 3
Tooth Height	A_{min}	A_{avg}	A_{max}
Tooth Top Length	B_{min}	B_{avg}	B_{max}
Grid Density	C_{min}	C_{avg}	C_{max}
Laser Power	D_{min}	D_{avg}	D_{max}
Laser Speed	E_{min}	E_{avg}	E_{max}
Overhang Angle	F_{min}	F_{avg}	F_{max}

To validate the optimisation results, a case study of an artifact consisted of various overhang areas will be printed twice by using default and optimised support structures.

Progress and Expectations

So far, the Design of Experiments (DoE) concerning the first round of printings has been analysed. Future work includes the completion of the printings and the outputs' measurements to collect the data that will be analysed, visualised, and optimised. The expected results of this research are to develop an innovative platform for effortless, reliable, and sustainable AM, capable of detecting the critical areas of an imported object where supports are needed and proposing optimised support structures for each specific area.

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Supervised by
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Behavioural cloning for robotic manipulation tasks with complex dynamic interactions

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Background

Robotic systems are extensively used across multiple industries to undertake tasks that require speed, precision or forces that are beyond human capacity. However, there is still a vast range of processes where manual labor is the only option due to extremely complex dynamic interactions requiring control strategies that are impossible to program into a robotic system.

Imitation learning techniques can enable agents to learn to perform tasks directly from expert demonstrations [1] without requiring explicit control strategy design. This opens up a huge array of applications where human operators are still required to be involved even though the tasks performed are extremely tedious, low-value and with significant health & safety risks.

Most of the research work around Imitation Learning, however, is overwhelmingly focusing on tasks and agents that accommodate one or more of the following assumptions: (i) existence of high-number of expert demonstrations or capability to perform lots of iterations to learn the task [1], [2], (ii) that access to the full state of the task is available [3], (iii) that the task can be accomplished purely by taking care of the kinematic rather than the dynamic aspects of the environment [4].

Such requirements however can be difficult to meet in real-world tasks, particularly in cases encompassing highly complex contact interactions such as in soft fruit picking (agriculture) and assembly/disassembly of complex devices (manufacturing).

Objectives

The objective of this work is to enable Imitation Learning on tasks with complex dynamic characteristics. The case in point is fresh mushroom picking which is notoriously difficult to master even for human operators; mushrooms are very easy to damage during picking, requiring months of training for a human picker to meet industry standards in terms of productivity and quality.

Methodology

A robotic gripper and a mushroom have been modelled in a sophisticated simulation environment based on the *PyBullet* engine. The roots of the mushroom are modelled with linear and rotational spring-damper systems. A set of 30 expert demonstrations involving a grasp-twist-lift sequence have been collected using carefully design control strategy. Solving this task is difficult as it requires the agent to apply delicate forces on the mushroom cap while ensuring that the mushroom does not slip. Imitation Learning happens purely from visual streams and force measurements, so that no knowledge of the internal state is revealed to the agent. The images are passed through a Variational Autoencoder (VAE) [5] to learn latent embeddings. A Behavioural Cloning approach is employed where the embeddings, with the force measurements concatenated, are fed into a Multi-Layer Perceptron network to learn a control policy.

The models are first trained on observation and action pairs derived from the recorded expert trajectories starting from random positions close to the mushroom and then tested on new task instances.

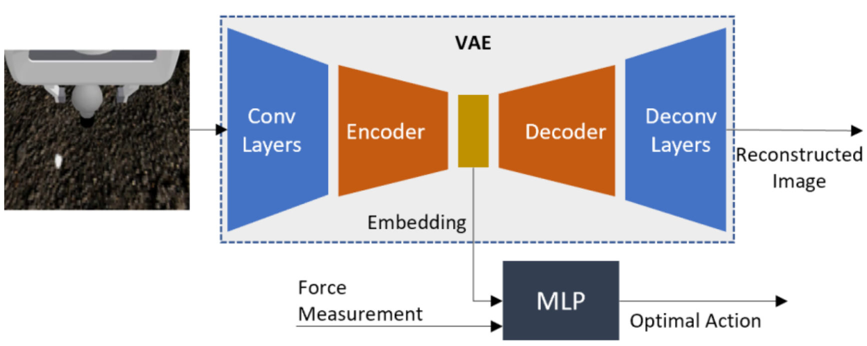

Fig. 1 Behavioural Cloning Architecture

Results and Future Work

The current approach achieves promising results; it can solve the task over 70% of the time, while trained on <20 demonstrations. The models used are exceptionally small; the VAE and the MLP only feature 6 and 2 layers respectively allowing inference to happen within 1.5ms on a CPU, which is important for real-time robotic control while leaving margin for increasing model complexity. The trajectory of the trained agent closely matches that of the expert with reasonable lag and the delicate force requirements are respected, as seen in Fig. 3. The next steps is to improve performance in terms of success rates and task accomplishment speed through careful model hyperparameter tuning in terms of layer sizes, learning rates etc.

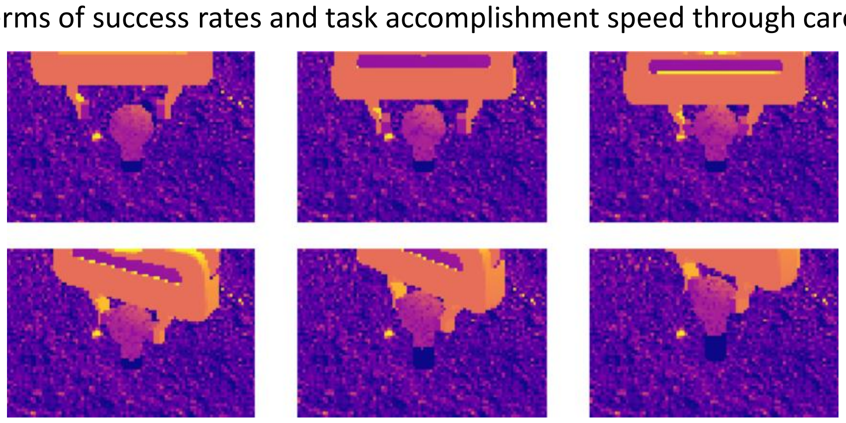

Fig.2 Screenshots during successful task accomplishment by the trained agent

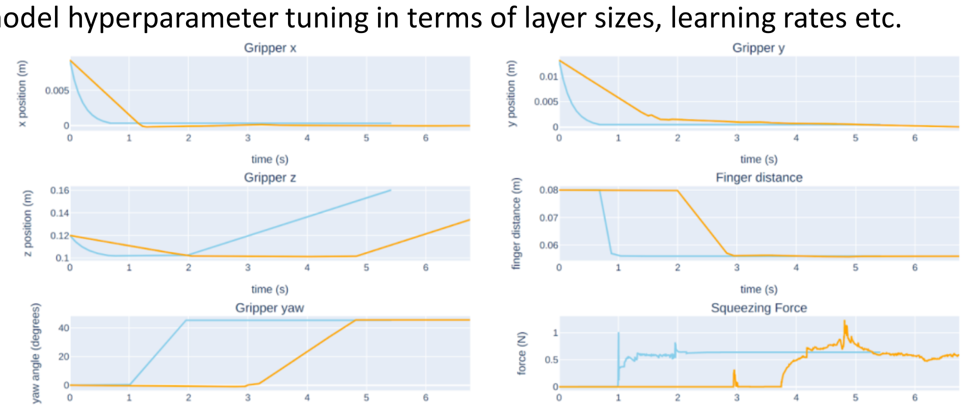

Fig.3 Gripper trajectory and force (Orange: trained agent, Cyan: Expert Agent)

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Design of materials and welding joints for hydrogen service

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Background

- Hydrogen being the future fuel, development of materials for its generation, transportation and storage is crucial
- Materials used for storage of hydrogen are known to be sensitive to hydrogen embrittlement
- Hydrogen embrittlement(HE), known as hydrogen assisted cracking or hydrogen-induced cracking, is the embrittlement of a metal by hydrogen
- Hydrogen diffuses through metals and increases the likelihood of hydrogen embrittlement at temperature below ~150 °C

Objective

- To enhance the understanding of hydrogen embrittlement, hydrogen adsorption, absorption and diffusion in metals
- To characterise the mechanism and to obtain key data of the above mentioned processes using electrochemical permeation analysis using Devanathan- Stachurski (DS) cell
- To design HE-free new welding joints using the data obtained from permeation study

Proposed Methodology

I will commission and make use of the Devanathan- Stachurski (DS) cell at TWI , and the DS cell will measure diffusivity of hydrogen by analysing hydrogen into the metals when exposed to gaseous environment[2], through the following processes:

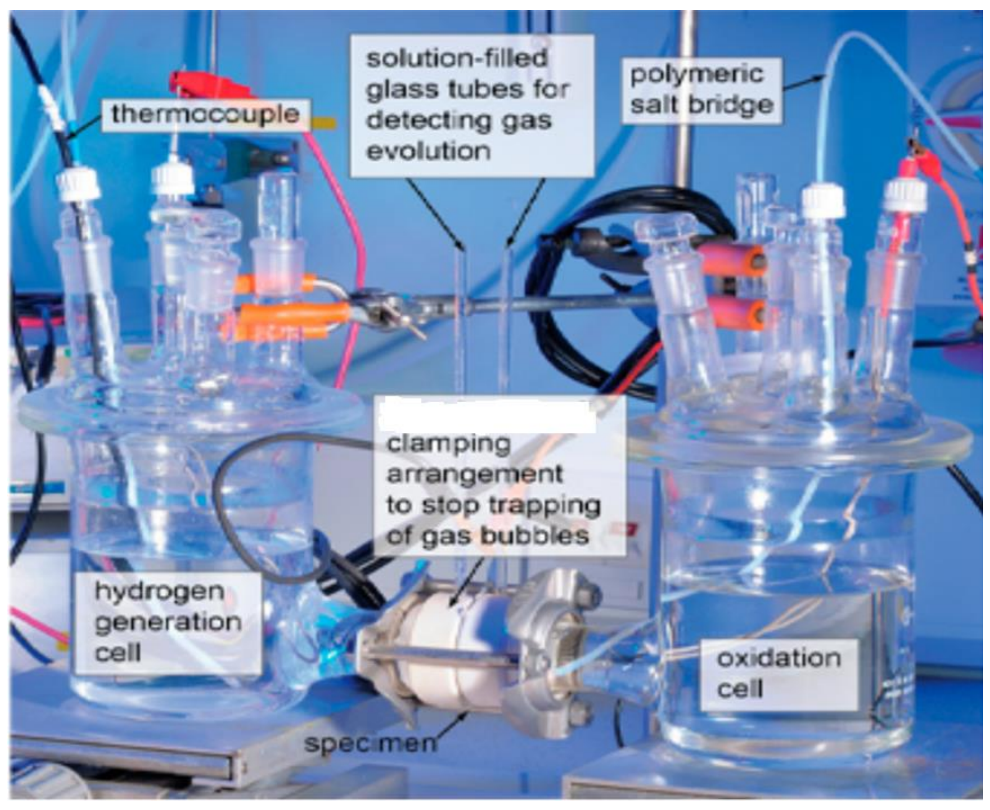
i. H_2 reaches the metal surface, gets polarized by the surface electrons and is then physisorbed on the surface

ii. Physisorption results in metal electrons populating the anti bonding molecular orbitals of H_2 , weakening the H-H bond, and H_2 dissociates

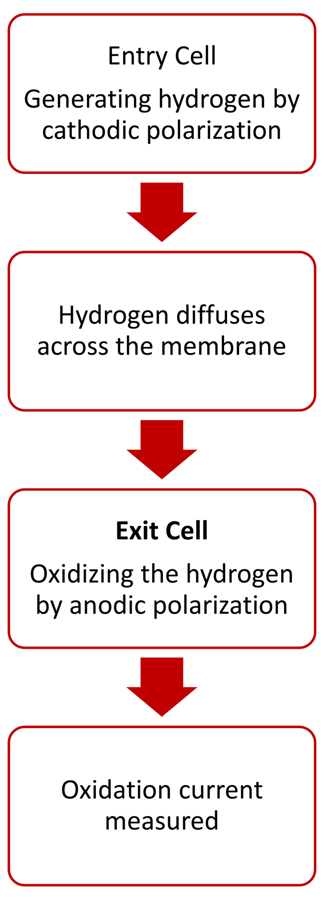
iii. Dissociated H atoms are chemisorbed on the metal surface and are absorbed into the bulk of the metal

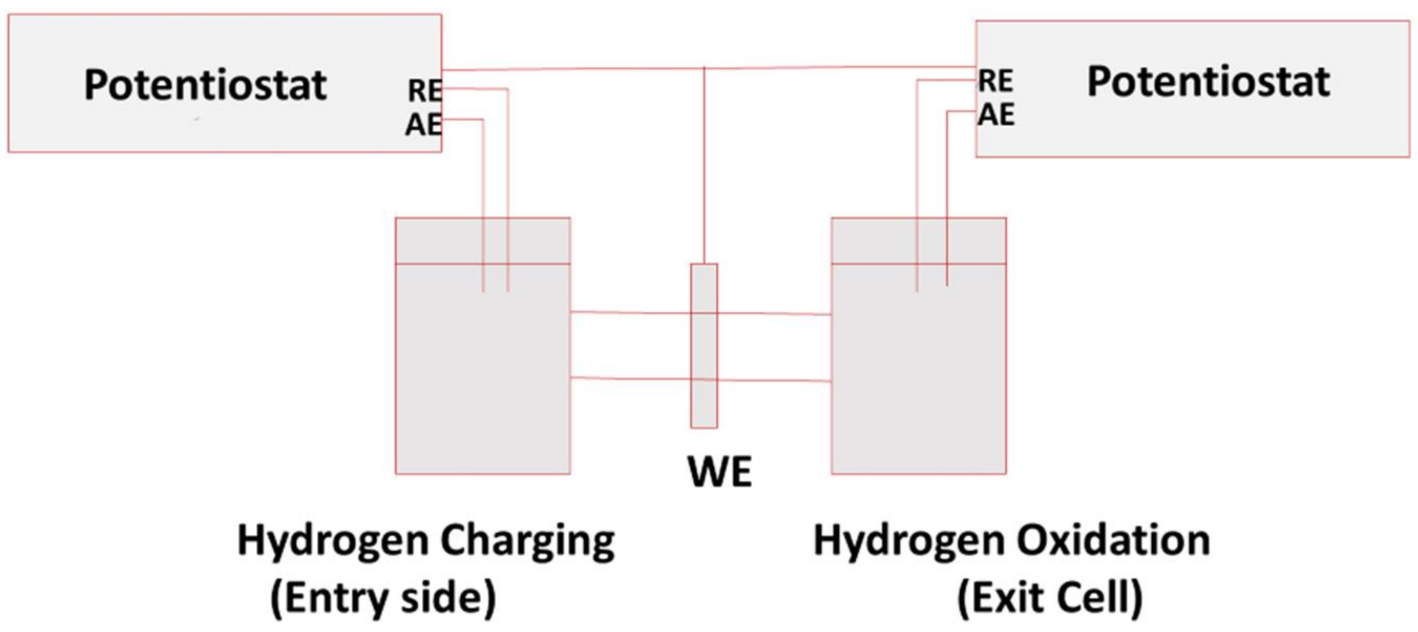
iv. Absorbed hydrogen atom diffuses through the bulk of the metal and increases the plausibility of hydrogen embrittlement

- Diffusivity of hydrogen is measured electrochemically using DS cell[1]



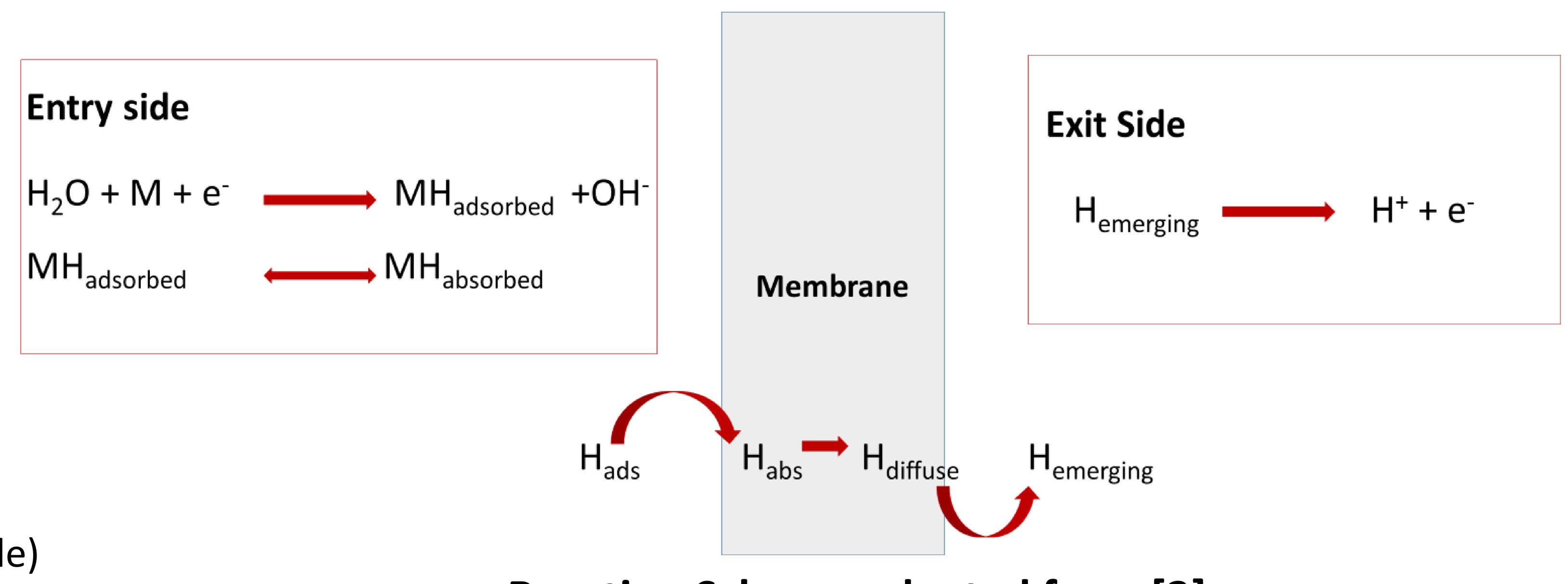
DS cell picture from TWI Ltd





Schematic diagram of DS cell set up

(WE – Working electrode, RE –Reference electrode, AE – Auxiliary electrode)

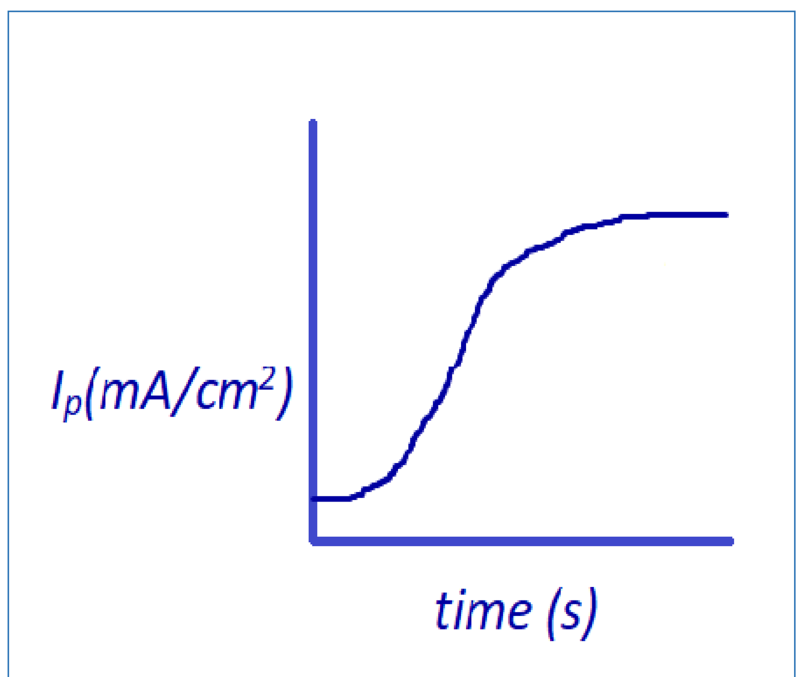


Reaction Scheme adapted from [3]

[H_{ads} – Adsorbed hydrogen, H_{abs} – Absorbed hydrogen , M- Metal, MH- metal hydride]

Expected Results

To obtain H permeation rate, effective H diffusivity and apparent H solubility from measured permeation curves



Typical hydrogen permeation curve

Hydrogen permeation rate (P)

$$P = J_\infty L$$

L is the thickness of the specimen

Effective hydrogen diffusivity

$$D_{eff} = \frac{L^2}{6t_l}$$

Steady state hydrogen flux (J_∞)

$$J_\infty = \frac{I_p^\infty}{nF}$$

Apparent hydrogen solubility

$$C_{app} = \frac{J_\infty L}{D_{eff}}$$

I_p^∞ - steady state current density

n - number of electrons transferred

F - Faraday's constant

L -thickness of the specimen

t_l - lag time

Potential Impact

- Understanding the gaps in hydrogen diffusion behaviour in various metal
- To design a new material with low hydrogen diffusivity and high resistance towards hydrogen embrittlement,
- To design HE-free new welding joints using the data obtained from permeation study

Acknowledgement

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Optimisation of Extreme High-Speed Laser Application (EHLA) In Use For Coatings

NSIRC Conference 2022

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Background

During a component's lifetime, it can be subjected to many environments that can adversely affect its performance. A cost-effective solution of improving functionality and extending life is to apply a coating. There are currently multiple deposition processes to deposit these coatings: thermal spray, hard chrome plating, plasma spray and traditional laser cladding. However, these processes have some inefficiencies including high dilution, porosity and low bond strength to the parent material. This can be in addition to cost, health concerns and high quantities of material waste. A replacement coating technology is needed to address the issues listed above.

EHLA has been identified as a promising deposition method. The pre-melted state of the powder allows for the process to have increased speeds of >150m/min. This is a key enabler for increased productivity/efficiency over existing technologies that require coatings in the range of 20-300 microns thickness.

Aims and Objectives

This project's aim is to optimise the input parameters and analyse the outputs to determine the suitability of the EHLA process for coatings and assess its use for industrial applications.

- To research competing technologies
- To identify suitable candidate material(s) & coating(s) for EHLA studies
- To investigate effects of EHLA input parameters for Inconel 625 onto substrates and the resultant material properties
- To characterise materials and evaluate applicability for industrial applications
- To compare and analyse EHLA outputs with competing technologies

Workplan

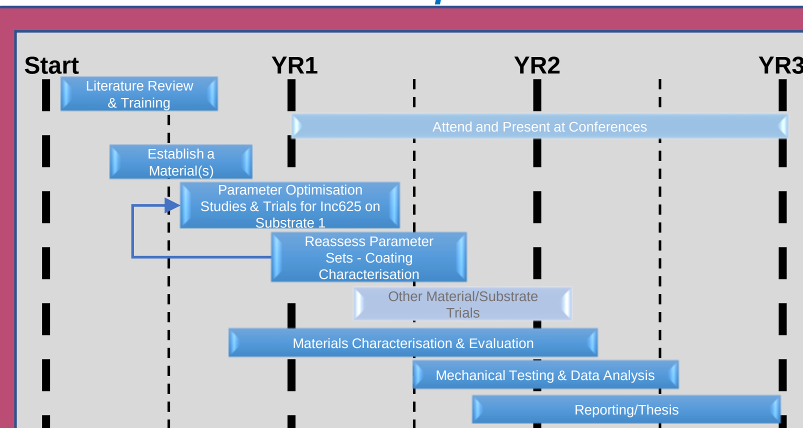

Figure 2: Planned Structure of PhD Project

The Process

The EHLA process is an extension on traditional laser cladding, the main difference being how the process inputs the powder. The powder is fed through a coaxial nozzle a few mm's above the surface, into a focussed laser beam (see Figure 1).

For traditional laser cladding, the powder is melted at the surface of the substrate (Fig1a). For EHLA, the powder is pre-melted before reaching the surface (Fig1b). This means that (compared to laser cladding), EHLA creates a minimised heat input to the substrate, resulting in a much lower HAZ and lower dilution.

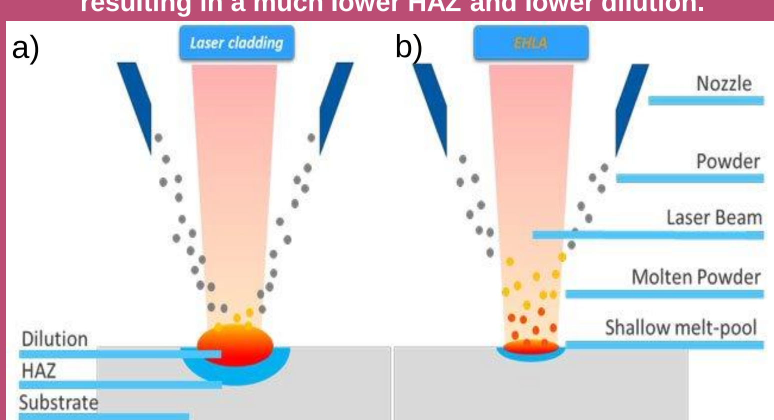

Figure 1: Schematics of traditional laser cladding (left) compared with the EHLA Process (right) (TWI, n.d.)

Different parameters can affect deposition properties (microstructural and mechanical). Therefore they need to be properly assessed to establish which parameters have what effect upon the final coatings, and by extension, whether EHLA can outperform other processes in terms of performance, cost, delivery and efficiency.

Potential and Future Applications

The EHLA Process, is being looked at within industry to potentially replace existing technologies (see Figure 3).

Hydraulic cylinders (see Fig3a) currently use hard chrome plating, a method which now has been labelled too hazardous to health (due to the hexavalent chromium used in the process). As a result, EHLA has been identified as a much less hazardous, effective and cheaper alternative for the future. Furthermore, some car companies are currently trialling EHLA to replace thermal spray techniques used upon brake discs (See Fig3b) as they look to reduce carbon emissions from the discs.

a) b)

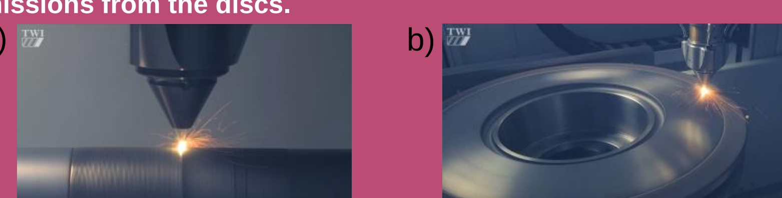

Figure 3: a) The EHLA process coating a hydraulic cylinder (TWI, n.d.) b) EHLA coated brake discs (TWI, n.d.)

For the future, use of EHLA could aid many sectors of industry, from use upon bearing journals, valves and stems, and other concentric applications to eventually the potential to surpass the dimensional weakness. Though the speed would unlikely reach the same efficiency, the ability to program the laser to undertake coatings upon non-concentric parts could also be worth investigating.

Contribution and Research Impact

My research will deepen understanding of EHLA in the following ways:

- Quality/Performance – microstructural characteristics (i.e. dilution, porosity), wear/corrosion resistance, process repeatability
- Cost/Economics – productivity/processing times, reduced waste, equipment/capital expenditure etc.
- Delivery – process efficiency, need for post-processing
- Health, Safety & Environmental considerations – *REACh compliance and regulations (in comparison to hard chrome plating process)

This research therefore provides an exciting opportunity to explore the EHLA technology and further understand its key characteristics and assess its applicability for a variety of industrial uses and applications. Additionally, the research will also provide a good guide in the search for a replacement to chrome plating.

References and Acknowledgements

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*REACh Registration Evaluation Authorisation and Restriction of Chemicals

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Bridging the Simulation to Reality Gap in Robotics (Sim2Real)

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supervised by

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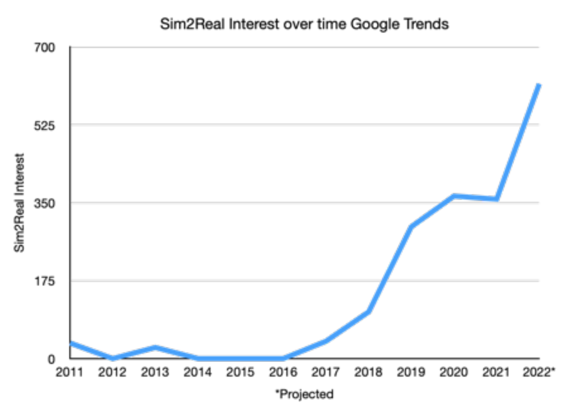
Introduction

In 2012 the work of Krizhevsky et al. "ImageNet Classification with Deep Convolutional Neural Networks" marks the dawn of a new era with the so-called "deep learning revolution" and marks our current period. A departure of "hand-made" manual feature engineering proved to be an extremely powerful idea allowing deep-network architectures inspired by the human vision cortex to be tuned entirely from labeled data through back-propagation. Since then such architectures completely dominate the field. Necessary ingredient for achieving such performance is a vast amount of labeled data which can be hard & expensive to be retrieved in the real-world. Synthetic data generation from artificial environments can be a good starting point for training with complementary specialized domain-adaptation techniques assisting only for transferring & deploying such systems to the real-world. Domain-adaptation techniques can also be used to repurpose systems that have been trained to different domains.



The breakthrough "end-to-end" application of deep network architecture for dynamical systems & decision making processes was not that straightforward and came a little-bit later in 2015 with the so-called Deep Q-Learning from DeepMind which was able to solve Atari games directly from pixels-to-action, a long standing request in robotics. Again the training process requires a great amount of training sessions "epochs" with trial-failure attempts (Reinforcement Learning) to achieve a good performance. Performing these training session in real-world systems is often extremely slow, expensive & potentially hazardous as well, bringing the need for synthetic data-generation again at the forefront.

In an ideal scenario we should be able train our agents fast & reliably in a simulated environment and directly deploy them to our real-world application. In 2016 Sadeghi & Levine with their work "CAD2RL: Real Single-Image Flight without a Single Real Image" manage to do exactly that. Domain-Randomization, namely strategically changing model parameters during the training seems to generate robust agents that are able to cope with the noise and discrepancies of the real-world without requiring extremely sophisticated & accurate simulation environments. Inserting noise and randomness in model based design & control engineering is not an entirely new concept and has been used extensively in system engineering for testing & fine-tuning purposes. The key-difference again in the Reinforcement Learning context is the attempt for automatic feature engineering in an "end-to-end", "pixel-to-action" context.

In the same context OpenAI achieves outstanding performance in robotic manipulation by solving a Rubik cube purely in a simulated environment. This unprecedented dexterity brings the sim2real in the forefront as a standalone ontological entity.

A taxonomy on Sim2Real

Based on the survey papers mentioned above and set of independent additional scientific sources on the topic, either direct or indirect, an early attempt to establish a taxonomy on the Sim2Real specific techniques was attempted.

- Domain Randomization.
- Domain Adaptation.
- Explicit Transferable Abstractions.
- Real2Sim.
- Differentiable Simulation.
- AI-Enhanced Physics.
- Zero-Effort Sim2Real.

Simulation Framework

University of Essex is an official partner in the EU Research Project "SoftGrip"[1] aiming to automate the delicate & demanding task of mushroom out-rooting with the combination of Reinforcement Learning & Sim2Real techniques. We started by developing a simulation framework that is capturing essential environmental dynamics by focusing especially in simple failure modes for the mushroom root. We borrow elements from material science and we implement a static model based on the Von Mises failure mode in the case of a homogeneous tubular beam under axial P, bending M & torsional T loads.

$$\sigma_x = \frac{P}{A} + \frac{Mc}{I}, \tau_{zx} = \frac{Tr}{J}$$

$$\sigma_{VM} = \left(\sigma_x^2 + 3\tau_{zx}^2\right)^{1/2}$$

Out-rooting will occur when the total applied strain exceeds the tension test yield strength:

$$\sigma_{VM} > S_y$$

We utilize the PyBullet physics engine and we model the root of the mushroom as a combination of a PD controlled ball-revolute-prismatic joint system. By properly tuning the proportional terms of the PD controllers we can emulate the axial, bending & torsional stiffness (modulus terms).

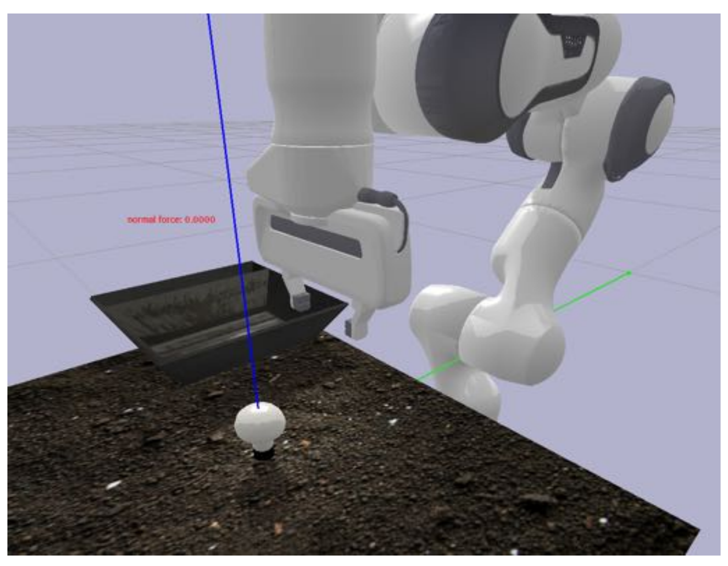


Figure: Gym Simulation Environment for Mushroom Out-rooting training.

Deployment Strategies

It should be pointed out that robotic manipulation tasks are notoriously difficult to simulate and they rarely transfer well in the real-world. The reason mainly be the unpredictable highly non-linear nature of contact & friction dynamics and interactions in a multi-body dynamics context. Our current strategies focus into combining simulation parameter-fitting through a differentiable physics engine, domain-randomization during training and explicitly learning the real-world action dynamics of the robot manipulator.

Figure: Real-World evaluation setup based on the Franka Panda Robot an Intel Real-Sense D455 RGB-D camera & 3D printed mushrooms.

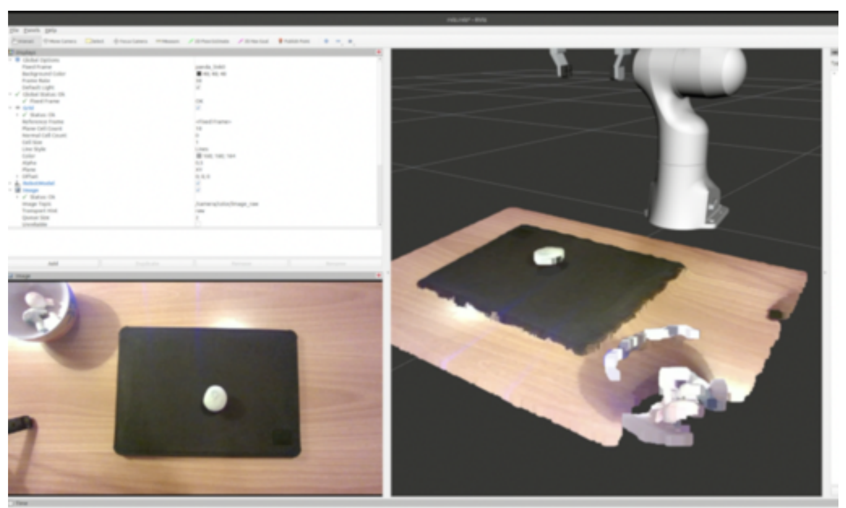


Figure: Visualizations in rviz with the image and point-cloud delivered from the Intel Real-Sense D455 camera.

Future Work

Our work currently focuses in improving Domain-Randomization strategies by formally selecting critical simulation parameters based on the manipulation task and thus improving training speed. The agent's sophistication goes hand-in-hand with the complexity of it's environment, we therefore applying continuous curriculum-learning as an intermediate step before real-world deployment. Ultimately our current belief is that the problem of sim2real is ultimately a result of the lack of hierarchical representation in the current Reinforcement Learning architectures. This is a long-standing quest the field of Reinforcement Learning and it is believed to be one of the key ingredients for achieving true & general artificial intelligence.

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softgrip-project.eu.

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Laser Ablation of Mild Steel by 50 W Nanosecond Pulsed laser: Effects of Laser Head length and Laser Scanning Speed

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Introduction

This article examines the process of laser ablation on mild steel by considering the rate depth and roughness of the removed areas. The laser used in this research is a low-power nanosecond laser with a maximum average power of 50 watts. The distance of the samples from the laser head (working distance) was varied at two lengths of 180 and 200 mm. Laser scanning speeds were evaluated at four different rates (between 298 mm/s to 1473 mm/s). Laser power and waveform were considered as constant parameters for all samples. In this study, design of experiment was applied to optimize the experiments and it predicted the input and output parameters for the optimum samples.

Aim

Study the effects of working distance and laser scanning speed on the roughness and depth of the laser ablation process. By remote-handling the procedure, this method can be a reliable way to remove some radioactive waste from nuclear facilities. Also, changing the waste forms and storing them in small filters can be safer and cheaper than traditional methods. Additionally, the laser beam can operate faster than water and chemical decontamination techniques temperature because of the beam's inherent properties.

Objectives

- Decreasing the roughness
- Increasing the depth of the laser ablation process
- Creating a uniform surface texture after the process

Experimental work

- ***Laser:*** nanosecond laser (average 50 watt power)
- ***Scanner:*** Raylase (SS-10)
- ***Material:*** Mild-steel (S275JR)

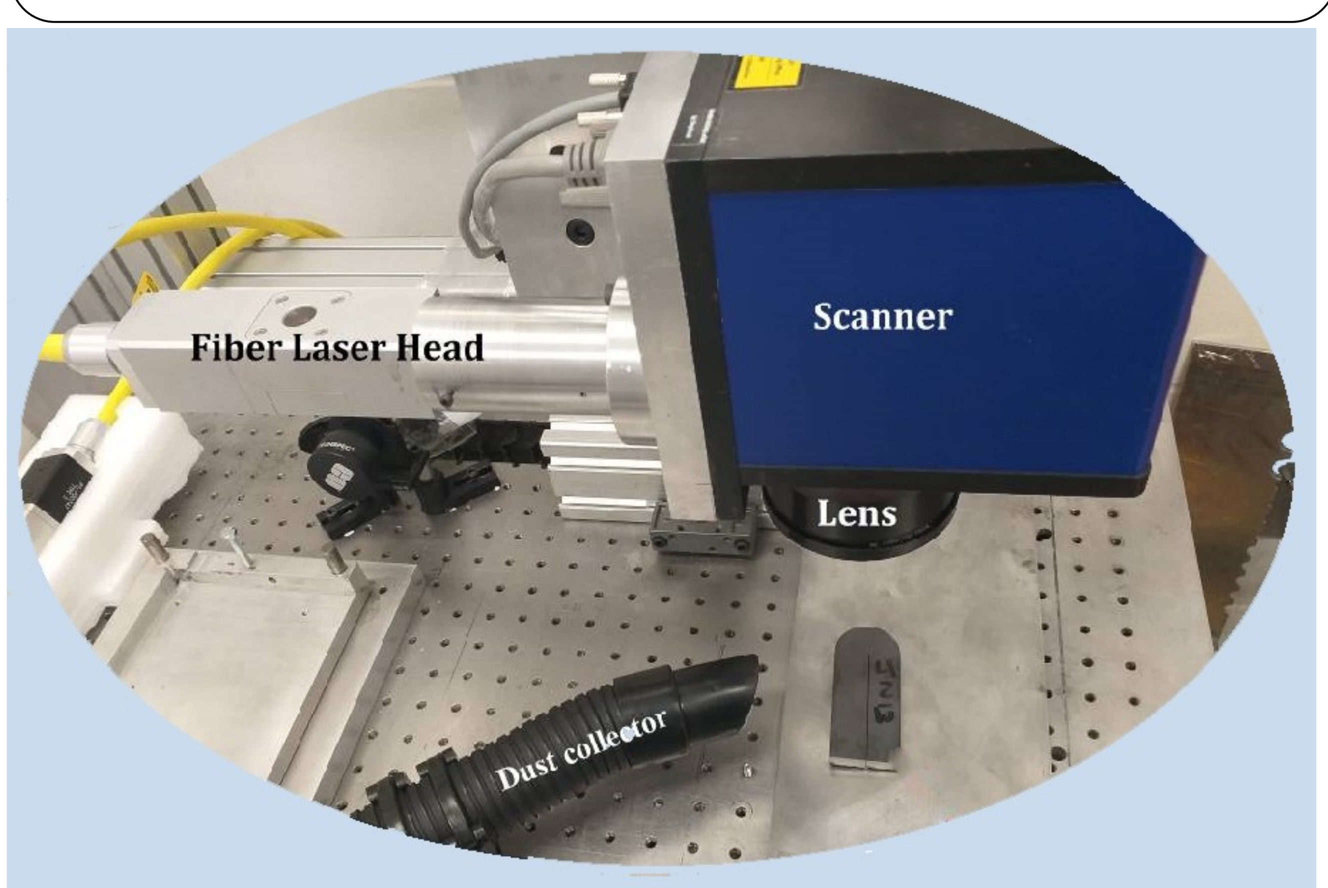
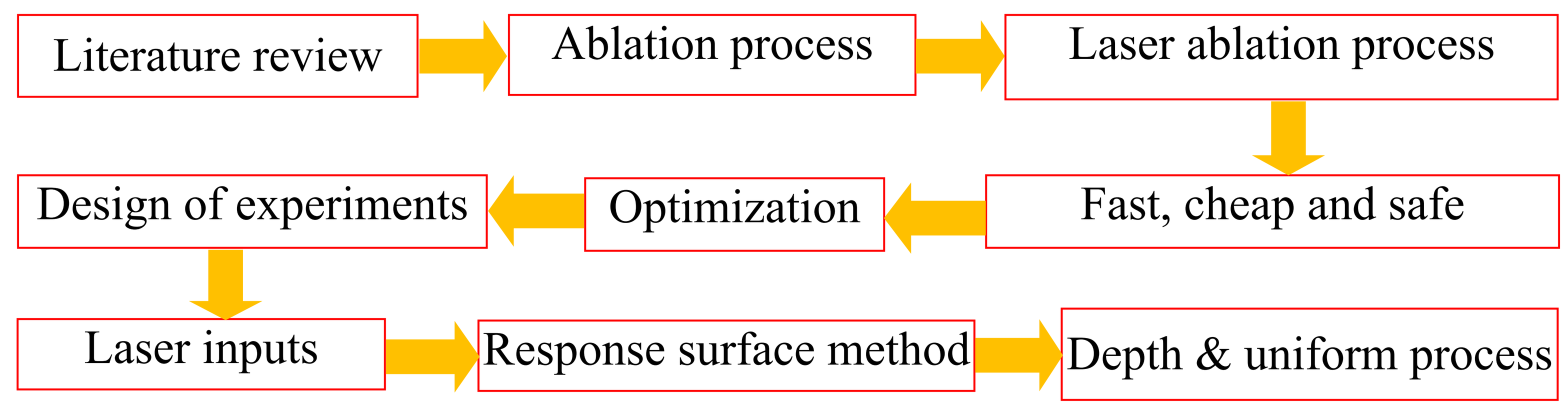


Figure 1. Laser ablation setup

Table 1. Laser ablation input and output

No.		Inputs: Wave-Form	Number of pass	Scanning Speed	Degree of Hatch A	Degree of Hatch B	Outputs: Roughness (μm)	Depth of material removed (μm)
WO1	Predicted	37	9	350	45	45	4.8	74.7
	Real						4.3	69.2
WO2	Predicted	19	4	760	0	90	1.2	30.2
	Real						1.4	33.5
ZO1	Predicted	16	8	490	90	45	5.1	68.4
	Real						5.5	78
ZO2	Predicted	34	6	360	45	0	3.4	38.7
	Real						2.8	35.4

Methodology



Results

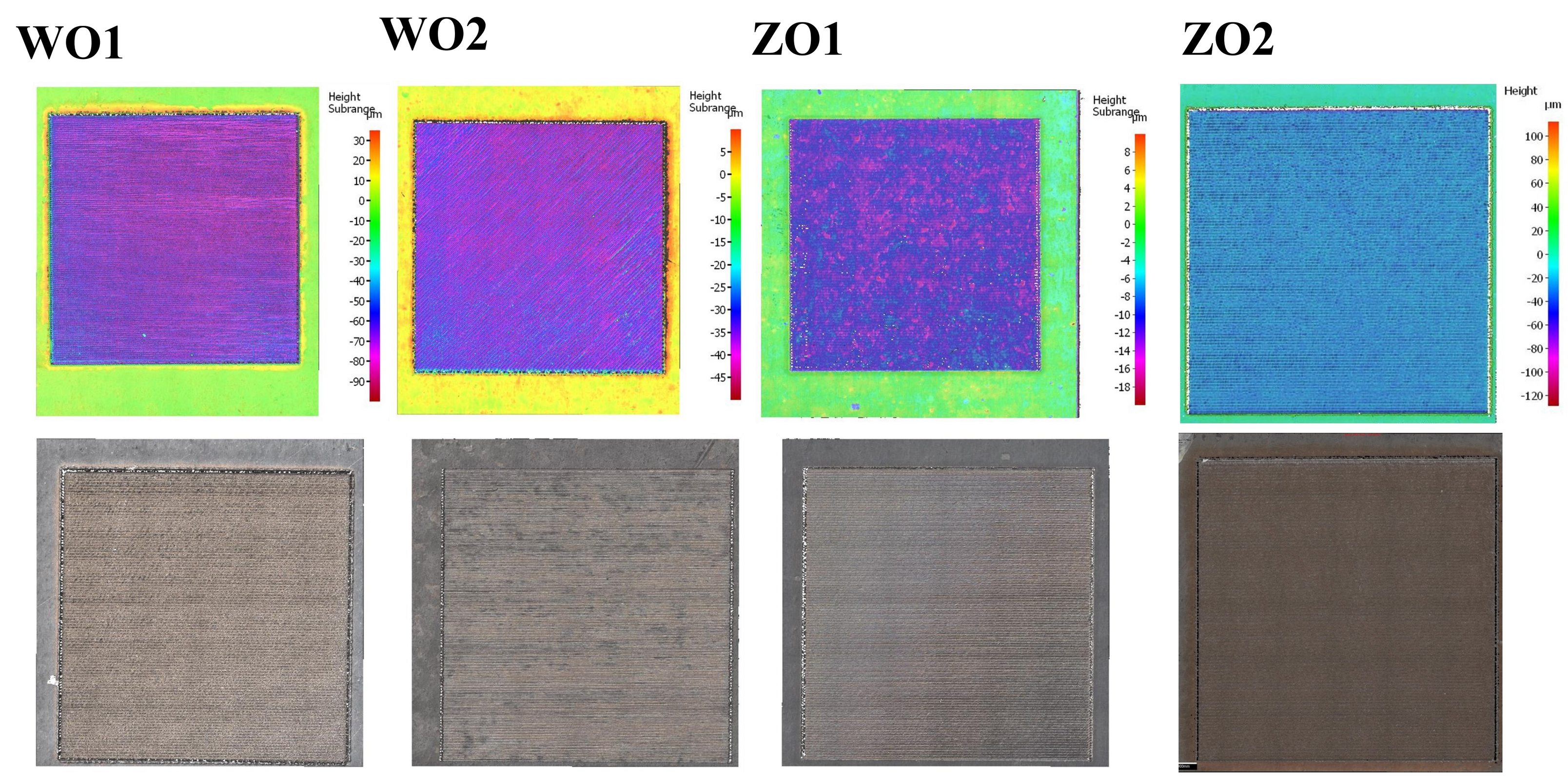


Figure 2. Samples profiles of the laser ablation

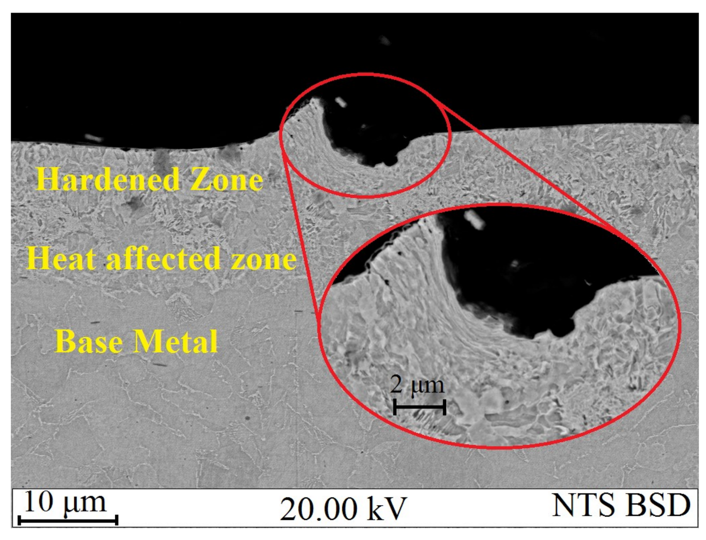


Figure 3. Microstructure of the ablated zone

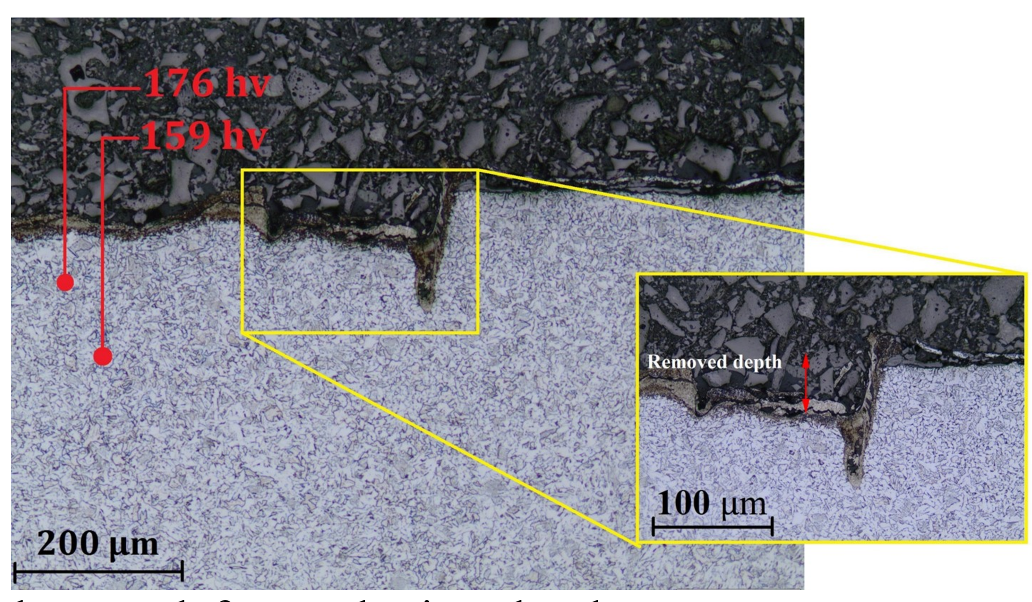


Figure 4. Under-cut defect and micro-hardness test.

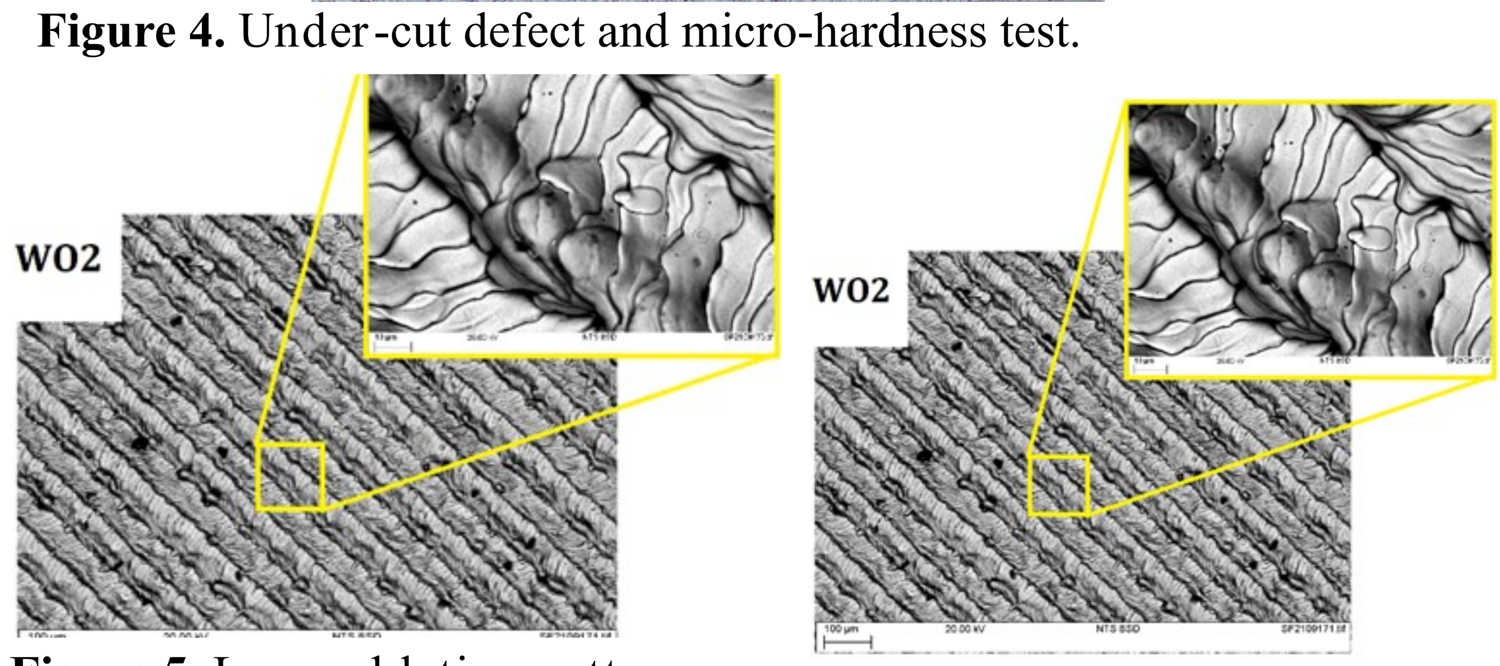


Figure 5. Laser ablation patterns

Conclusion

The results show that with an increase in the speed of laser scanning, the amount of material removal from the surface decreases due to a reduction in the time of interaction of the laser with the surface. It was also found that increasing the working distance increased the surface roughness due to the increased size of the laser spot. Also, a limited amount of microstructural change from the ferrite-pearlite phase of the base metal to martensite was observed.

Acknowledgment

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College of Engineering, Design and Physical Sciences
Department of Mechanical and Aerospace Engineering

Magnetic-Based Approach For Characterization of Pipelines Corrosion

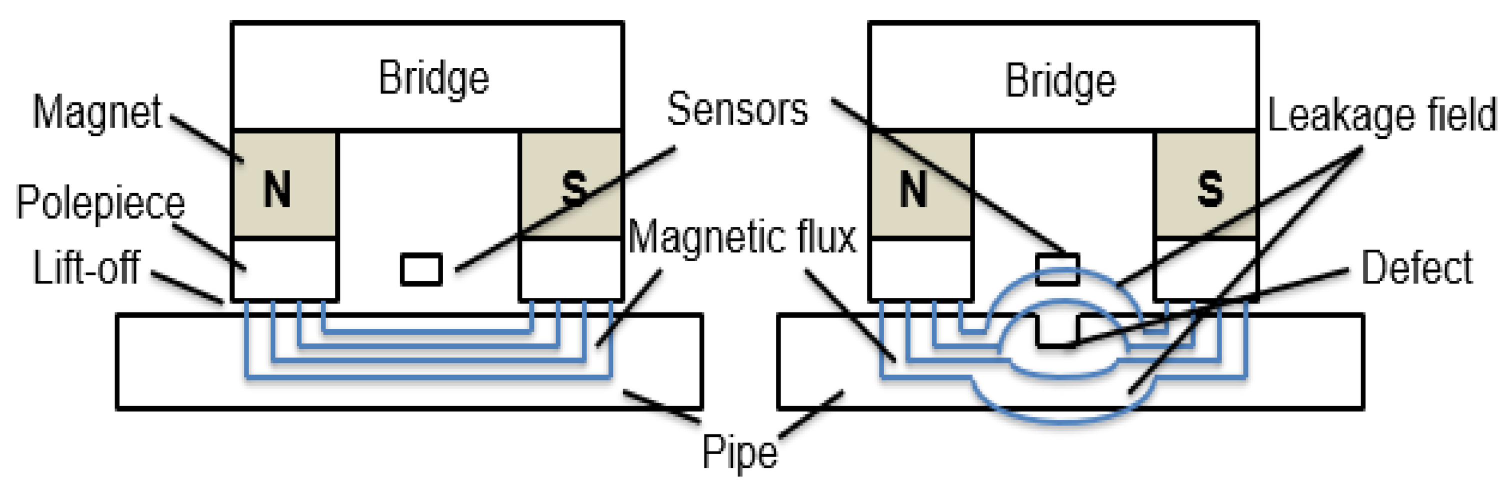
Selamawit Abate (Doctoral Researcher)

Supervisors: Dr Nenad Djordjevic, Prof Rade Vignjevic, Brunel University London
Mr Owen Rees-Lloyd, TWI Ltd

1. Background

- Steel pipes are used to transport oil and gas. However, they are prone to corrosion and degradation.
- Many non-destructive testing (NDT) techniques have been developed to detect corrosion and prevent catastrophic failures.
- Magnetic flux leakage (MFL) is an efficient NDT technique.
- The magnetic circuit is a main component of MFL.

When MFL is used on a corrosion free pipe sample, all of the magnetic flux will pass through the pipe. However, when corrosion is present, there will be magnetic flux leakage, and a sensor will detect this leakage field.



Magnetic circuit without defect *Magnetic circuit with defect*

2. Research Focus

- CorrSense is an MFL robotic device that can be permanently installed in areas of expected corrosion, such as pipeline bends where erosion-corrosion is common.

CorrSense [1]

Objectives:

- A redesign and parametric study of the magnetic circuit components in the MFL device.
- Investigating the comprehensive effects of multiple circuit parameters and pipe geometries.

Novelty:

- A practical approach for an efficient defect detection in pipes by all-inclusive optimization of multiple magnetic circuit parameters.

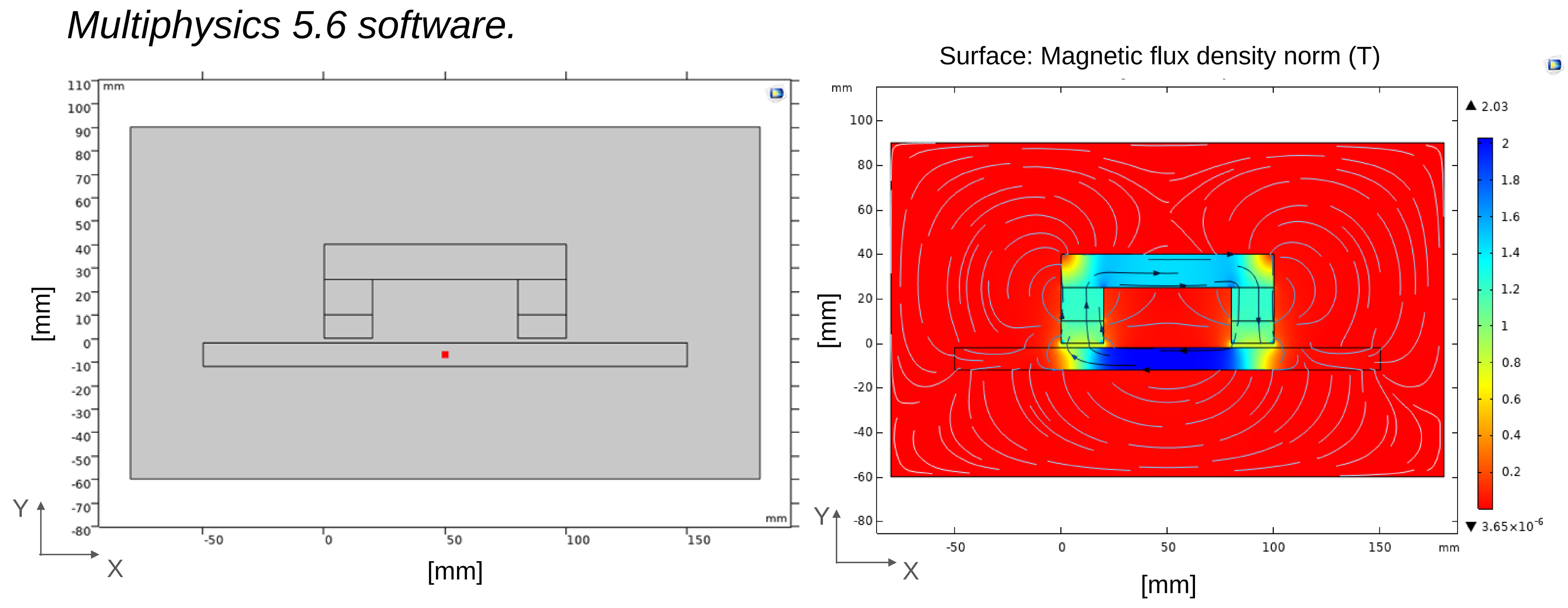
3. Methods

1. Simulation-led design, based on finite element analysis (FEA) using COMSOL Multiphysics 5.6 software.
2. Experimental work for the verification and validation of refined design.

4. Results

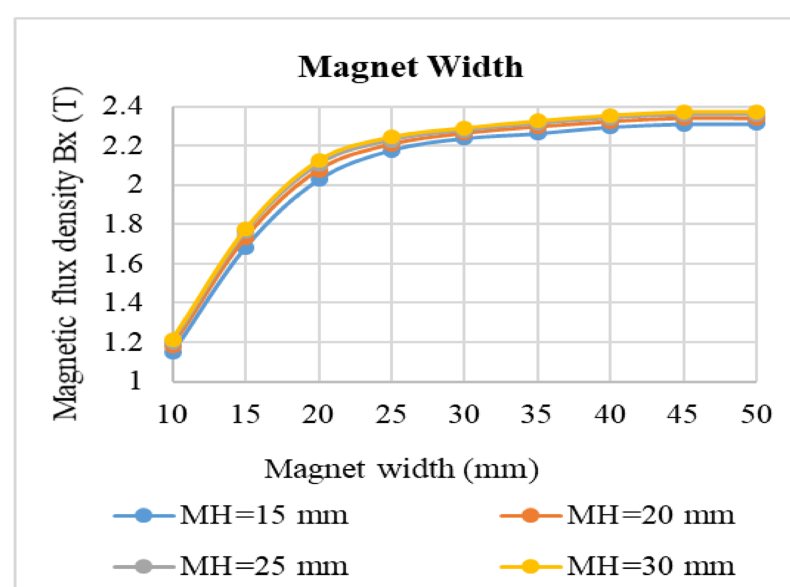
- Magnetization is the process of making materials temporarily or permanently magnetic. If the pipe is magnetized properly, it can leak enough flux in the presence of defects.

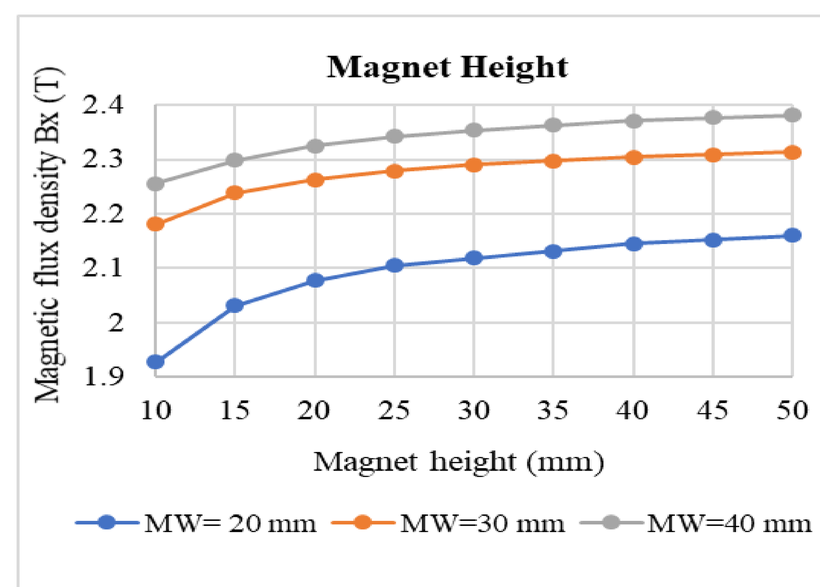
Magnetic flux density (Bx) behaviour in 2D FEA model, evaluated with COMSOL Multiphysics 5.6 software.



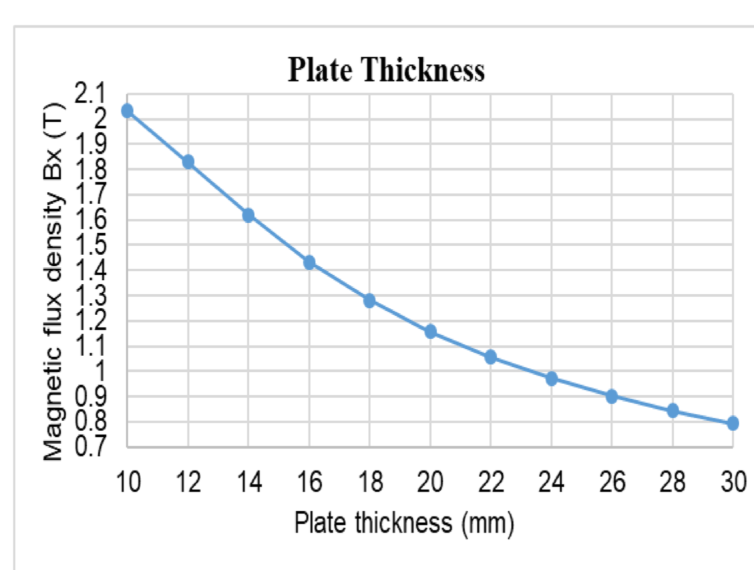
- Effects of circuit parameters' dimensions on the magnetization level:

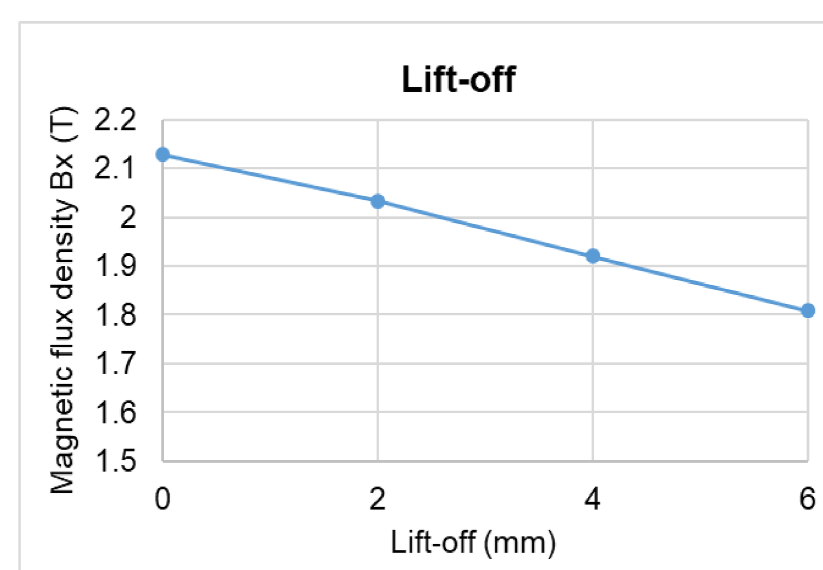
Bx increases sharply with increasing magnet width since the width determines the sum of magnetizing force along the circuit. In contrast, Bx increases slightly with increasing magnet height because increasing the height increases magnetic resistance.





Bx decreases with increasing pipe thickness and lift-off. Because while increasing the pipe thickness, a bigger magnet is required. And lift-off causes the distribution of flux outside the circuit.





5. Conclusions

- CorrSense is used to detect pipe bend defects.
- Magnetization has a significant role in defect detection.
- The circuit parameters' dimensions affect magnetization level. Therefore, optimal dimensions of these parameters are needed to enhance defect detection sensitivity.

6. Future Work

- Development of an optimization tool.
- Refined parametric and geometrical study.
- Experimental validation.

Acknowledgement

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Examination of Environmental Cracking in Additively Manufactured Materials

Yixiang Jin[1]

Background

Additive Manufacturing (AM) technologies are rapidly maturing and while basic properties such as strength and Charpy impact toughness are widely reported, the environmental cracking behavior is largely unknown. Environmental cracking mechanisms like stress corrosion cracking and hydrogen embrittlement are insidious failure mechanisms which occur where a susceptible microstructure is combined with a corrosive environment and stress, potentially leading to catastrophic failure and loss of life. Research is urgently needed to establish if AM materials behave similarly to traditional materials in terms of environmental cracking mechanism(s) and therefore identify if standard approaches to prevent these failures are appropriate for AM components.

Aims & Objectives

This project is now aimed to understand the hydrogen embrittlement behaviour of 316L stainless steels manufactured by laser powder bed fusion (L-PBF) processes and to compare it with wrought materials.

Oobjectives include:

- Identify if environmental cracking mechanisms observed are consistent with equivalent wrought/cast materials;
- Propose necessary adjustments to industry standards and standard test procedures necessary for AM materials/parts;
- Publish environmental testing data necessary to give industry confidence that current/new approaches are appropriate for AM material;
- Develop a mechanistic understanding of environmental cracking in AM materials.
- Identify if witness specimens deposited next to AM components are representative of actual parts, in terms of environmental crack susceptibility.

Future Works

Further literature research on L-PBF microstructure and hydrogen embrittlement is ongoing. In the following experimental stage, samples with different dislocation densities will be produced by controlling the process parameters and be tested under a hydrogen charging environment to study the interaction between hydrogen and the dislocation network.

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Current Research

This project started in early 2022, and is currently still in the literature research stage, a literature review is under working, and planning of experiments is ongoing.

Hydrogen embrittlement

Though there are several explanations for the mechanisms of hydrogen embrittlement, one basic fact is well-known: It is diffusible hydrogen which causes embrittlement.

A large factor that affects the diffusion coefficient is the defects in the materials. Defects have lower potential energy compared to lattice sites. Hence once hydrogen atoms enter, they will need to overcome a higher energy barrier to continue diffusing [1].

Microstructure of L-PBF materials

The high cooling rate and temperature variation during the L-PBF process provide unique microstructures (Fig. 1), including high and low angle grain boundaries, cellular solidification structures, dislocation networks, etc. (Fig. 2) and have superior mechanical properties compared to traditionally manufactured materials [3].

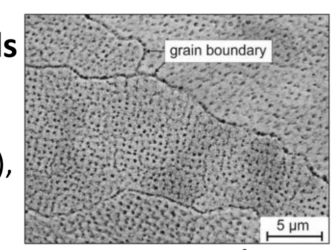

Fig. 1. Microstructure of L-PBF manufactured 316L steel. Licensed by CC BY 4.0. For more information see https://creativecommons.org/licenses/by/4.0/. Available at https://doi.org/10.1007/s00170-020-05371-1 [2]

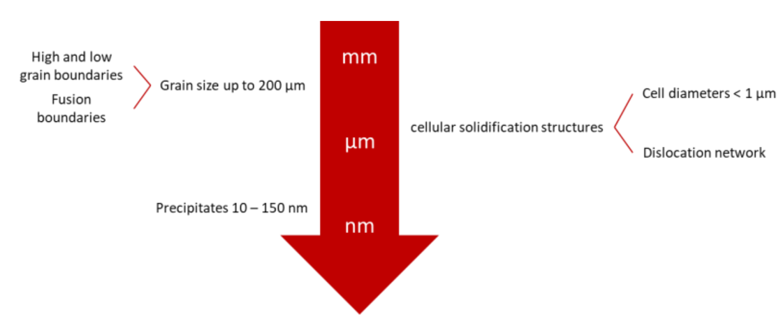

Fig. 2. Hierarchical structure of L-PBF manufactured 316L steel.

Hydrogen embrittlement in L-PBF materials

L-PBF processed materials have cellular structures formed by dislocation networks which are rarely found in traditionally manufactured materials. Such structure may have strong trapping effects on hydrogen atoms. The interaction between them could be a starting point to understanding the hydrogen embrittlement of L-PBF manufactured materials.

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[2] Röttger, A., Boes, J., Theisen, W. et al, Int J Adv Manuf Technol, Vol. 108, 769–783, 2020

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