

Model experiment for investigation of thermoelectric magnetohydrodynamics in metal additive manufacturing

--Manuscript Draft--

Manuscript Number:	JOMJ-D-25-00304R1	
Full Title:	Model experiment for investigation of thermoelectric magnetohydrodynamics in metal additive manufacturing	
Article Type:	Original Paper	
Corresponding Author:	Imants Kaldre, Ph.D University of Latvia Riga, LATVIA	
Corresponding Author Secondary Information:		
Corresponding Author's Institution:	University of Latvia	
Corresponding Author's Secondary Institution:		
First Author:	Imants Kaldre, Dr. Phys.	
First Author Secondary Information:		
Order of Authors:	Imants Kaldre, Dr. Phys.	
	Valdemars Felcis, Mag.Phys.	
	Ivars Krastins, Dr. Phys.	
	Peter Soar, Dr. Phys.	
	Catherine Tonry, Dr. Phys.	
	Andrew Kao, Dr. Phys.	
Order of Authors Secondary Information:		
Funding Information:	Royal Society (IES\R2\222050)	Dr. Andrew Kao
	Latvijas Universitate (5)	Dr. Imants Kaldre
	University of Greenwich (M3 For Impact)	Dr. Andrew Kao
Abstract:	Metal additive manufacturing is a rapidly growing technology revolutionizing many industries, yet wide adoption is limited due to the unreliability and complexity of the process. Scanning strategies, such as hatching, add further complexity to heat transfer and ultimately microstructure growth. Applying external magnetic fields is a promising technique to improve control of melt flow and heat transfer. High local thermal gradients can cause thermoelectric currents to circulate at the solid-liquid interface. When a magnetic field is applied, a Lorentz force drives fluid flow, which can have significant impact on the melt behavior and solidification outcome. In this work we analyze the impact a static magnetic field has on liquid metal flow using a scale model representative of additive manufacturing which allows us to directly observe and measure the thermoelectric magnetohydrodynamic flow. Experiments with bi-metallic bowl, made of two halves with distinctly different thermo-physical properties, provides an analogy to hatching revealing a strong influence on both thermoelectric currents and ultimately the flow. Through an analytic scaling analysis, the results are compared against numerical models spanning orders of magnitude in both length and velocity, providing a correlation between the model experiment and realistic conditions encountered in industry additive manufacturing processes.	
Response to Reviewers:	Response letter Model experiment for investigation of thermoelectromagnetic convection in metal	

additive manufacturing

Imants Kaldre^{1*}, Valdemars Felcis^{1,2}, Ivars Krastins^{1,2}, Andrew Kao², Catherine Tonry², Peter Soar²

¹ University of Latvia, Jelgavas street 3, LV-1004, Riga, Latvia.

² University of Greenwich, Old Royal Naval College, Park Row, London SE10 9LS, UK.

*Corresponding author: imants.kaldre@lu.lv

We are grateful to the reviewers for the assessment of our article and valuable suggestions for improvements. Replies to the comments are listed below:

Reviewer #1: This study offers a clear and well-rounded look at how thermoelectric magnetohydrodynamic (TEMHD) effects can influence metal additive manufacturing (AM). By using a combination of experiments on small-scale models and computer simulations, the authors explore how magnetic fields can change the way liquid metal flows in the melt pool during the printing process. Using both a Cobalt bowl and a bi-metal bowl setup, they show how the shape and materials involved affect the direction and complexity of these flows.

One of the most interesting parts of the study is the scaling analysis, which shows that TEMHD effects can become important even at relatively low magnetic field strengths—as long as there are steep temperature differences, which are common in AM. Even when the difference in electrical properties between solid and liquid metal is small, these flows can still play a major role.

What makes this work especially valuable is its real-world relevance. The results suggest that by adjusting the direction of the magnetic field, manufacturers could guide the flow of metal in the melt pool to improve how parts are built. This could be particularly useful for challenging print areas like corners, overhangs, or detailed features, and may help improve the quality and consistency of printed metal parts.

Overall, this is a strong contribution to the field. The experiments, simulations, and analysis all support the idea that magnetic fields could be a useful tool in improving metal AM processes.

I fully recommend the publication of this paper in its current form.

The authors thank the reviewer for their comments and appreciate that the key message around using and then scaling of the model experiment to real AM practices has benefit to this field.

Reviewer #2: This is a very nice paper reflecting a novel (proposed) solution to AM's challenges. The experiment gives a good basis for both asserting the validity of the model and extending the principle to AM.

We thank the reviewer for their overall summary of the paper and highlighting the benefit of the model experiment.

Since you assert that this technique may be used to reduced grain size and directionality in AM, I do wonder what the microscopy of your experiment looked like - did you see grain refinement?

The experiment is several orders of magnitude larger in length to 'real' AM processes and it therefore not possible to compare grain structures to the model experiment. The experiments were also performed with room temperature liquid metal to observe the flow patterns and no solidification took place, hence no grain structures were observed and so we do not discuss grain refinement in the paper. However, we agree that the benefits TEMHD promises could lead to grain refinement and indeed in the wider literature this has been seen.

The use of magnetic fields to cause grain refinement has been observed in many traditional processes. There is also now experimental evidence showing that the same is true in AM a result of TEMHD flows. It is concluded by many authors that forced convection refines grains in general. Our work focussed on understanding and

controlling the thermoelectric flows, which from these papers in the literature we infer will have an influence on grain structures.

We have added references into the manuscript along with a few words describing the grain refinement as a benefit. First to grain refinement in traditional techniques:

“... significant effect on the solidified metal [12, 13, 14] including beneficial effects like grain refinement [15, 16]”

Followed by AM specific papers:

“... AM with grain refinement also observed [17, 18]. Magnetic fields in AM have also been shown to address various problems such as precisely timed, exact size droplet ejection ...”

In the introduction, "AM is a clean and efficient technology due to minimal waste material ..." This is a controversial statement.

We agree that many current AM processes have not yet reached the level of efficiency as their equivalent, traditional, methods. However, the rapid growth and investment into AM technology seeks to reduce this gap in terms of energy and efficiency. Examples include (and by no means exhaustive), efforts to increase coupling (efficiency) between the laser and powder, recycling of powders and in our case melt flow control.

We have modified this sentence to be:

“AM has the potential to be a clean and efficient technology due to minimal waste material”

Please add a few more sentences introducing and explaining the Seebeck (thermoelectric) effect (Page 3, 3rd paragraph).

A more detailed explanation about thermoelectric potential and how it leads to current is added to the text. Text now reads:

“During AM extremely high local thermal gradients are present in the melt pool and nearby solid zone. Seebeck coefficient or absolute thermoelectric power can be different for liquid and solid metals. It is an electron transport property, and it can be discontinuous during phase change. If there is a thermal gradient along the interface, then a voltage difference is also generated along the solid-liquid interface.

Thermoelectric currents then circulate at the solid-liquid interface as a result of this voltage difference. The current originates from the Seebeck effect between solid and molten material, and its amplitude is proportional to temperature gradient, electrical conductivity of both materials and differential Seebeck coefficient between solid and liquid states of the metal.”

In discussions on the experiments with the bimetal bowl - further clarify the electric current directionality relative to the seam of the bowl. Unclear in several places in this discussion.

Our results show that with the Steel-Cobalt Bi-Bowl only one half of the bowl generates TE current. We have clarified the direction of the current at the position in the manuscript where the figure showing the current is discussed. The following text has been added when describing the figure:

“The figure shows that the current in the Steel is much smaller (practically zero) compared to Cobalt. There is no current between the Cobalt and the Steel and consequently the current passes along the seam (in the z direction) across the Cobalt – Galn interface. The current then circulates through the liquid Galn and back into the Cobalt. With no current in the Steel, there is no circulation between the Galn and Steel and the current is focussed in the liquid region above the Cobalt half of the bowl.”

Figure 5: It may be helpful to draw the seam in the bi-metal bowl over the figures to further clarify.

We have updated all the Figures include x,y and z on the axis to add clarity on the

directions. In Figure 5, the seam has been superimposed on to the results as a dashed line. The following text has been added to the figure caption:

“Seam is highlighted by horizontal dotted line with cobalt being the top part in all figures.”

Page 14-15 and Figures 7 and 8: It is asserted that "there is good agreement across all 3 solutions and the experimental data points." However, the plots do not reflect this well and instead appear that with scaling, the experimental results do not agree with the numerical or analytical model. (Between $B/B_c = 1-3$ in figure 7 and all experimental points in Figure 8).

We believe the reviewer is referring to the experimental data error bars falling outside of the analytic and numerical predictions. To give some more details, the error bars were calculated by taking a typical experiment and analysing the variation in measured velocities in the region of maximum velocity. We found the standard deviation of the velocity to be approximately 20% of the mean value. This the standard deviation is presented in the error bars presented in figures 7 and 8. However, this error only represents the 'measurement' error, and the true error is much harder to quantify. We are essentially comparing three different data sets (experimental, numerical and analytic) and there inevitably assumptions that arise between the three. For example, the geometry in the numerical model is idealised compared to the experiment, the model lacks a free surface, the temperature boundary conditions in the model are taken from measured experimental temperature data and the amount of liquid metal and acid are exact across all experiments. All of these will influence both the length scale and current density (indirectly through thermal gradient) and ultimately both driving and damping forces.

The focus of this paper is on the distinct difference between flow patterns based on magnetic field orientation that are consistent with predictions. Also, a direct comparison of the model experiment to AM conditions via an analytic solution with all three approaches lie within a single order of magnitude (the experimental data lies closer to a 40% error).

Therefore, our definition of 'good' agreement was factoring in both the qualitative flow structure and trends, along with the quantified scaling.

We have modified the paper to highlight that these 20% error bars represent the minimum error, and the true error is likely to be higher:

“The error bars in figures 7 and 8 are 20% of the measured value. This error was estimated by taking a typical experiment and analysing the standard deviation in velocity in a region of maximum velocity. This accounts only for the measurement error, but there are many other factors that are more difficult to quantify and so represents a minimum error.”

All authors have approved the revised manuscript and agree with its submission to JOM.

Imants Kaldre
23.04.2025

Cover letter

Model experiment for investigation of thermoelectric magnetohydrodynamics in metal additive manufacturing

Imants Kaldre^{1*}, Valdemars Felcis^{1,2}, Ivars Krastins^{1,2},
Catherine Tonry², Peter Soar², Andrew Kao²

¹ University of Latvia, Jelgavas street 3, LV-1004, Riga, Latvia.

² University of Greenwich, Old Royal Naval College, Park Row, London SE10 9LS, UK.

*Corresponding author: imants.kaldre@lu.lv

The article contains research work done by the authors in recent years. Work is done in cooperation between Magnetohydrodynamics technology laboratory of the University of Latvia and Applied Mathematics center of Greenwich University. Results presented in this work have not been published or submitted anywhere else. All photos and pictures are made by authors.

The article presents experimental setup and results, and numerical simulations of laboratory scale experiments on Thermoelectric magnetohydrodynamics. Experiment is designed to simulate various electromagnetic interaction on the additive manufacturing (AM) of aluminum alloys caused by static magnetic field. Work is done with the aim of developing the possible setup for application of magnetic field to metal AM. It is shown in the article that magnetic field can be the way to introduce strong melt pool size flow, which can affect heat and mass transfer leading to improved properties.

We confirm that neither the manuscript nor any parts of its content are currently under consideration or published in another journal.

All authors have approved the manuscript and agree with its submission to JOM.

Imants Kaldre



28.02.2025

Response letter

Model experiment for investigation of thermoelectromagnetic convection in metal additive manufacturing

Imants Kaldre^{1*}, Valdemars Felcis^{1,2}, Ivars Krastins^{1,2}, Andrew Kao²,
Catherine Tonry², Peter Soar²

¹ University of Latvia, Jelgavas street 3, LV-1004, Riga, Latvia.

² University of Greenwich, Old Royal Naval College, Park Row, London SE10 9LS, UK.

*Corresponding author: imants.kaldre@lu.lv

We are grateful to the reviewers for the assessment of our article and valuable suggestions for improvements. Replies to the comments are listed below:

Reviewer #1: This study offers a clear and well-rounded look at how thermoelectric magnetohydrodynamic (TEMHD) effects can influence metal additive manufacturing (AM). By using a combination of experiments on small-scale models and computer simulations, the authors explore how magnetic fields can change the way liquid metal flows in the melt pool during the printing process. Using both a Cobalt bowl and a bi-metal bowl setup, they show how the shape and materials involved affect the direction and complexity of these flows.

One of the most interesting parts of the study is the scaling analysis, which shows that TEMHD effects can become important even at relatively low magnetic field strengths—as long as there are steep temperature differences, which are common in AM. Even when the difference in electrical properties between solid and liquid metal is small, these flows can still play a major role.

What makes this work especially valuable is its real-world relevance. The results suggest that by adjusting the direction of the magnetic field, manufacturers could guide the flow of metal in the melt pool to improve how parts are built. This could be particularly useful for challenging print areas like corners, overhangs, or detailed features, and may help improve the quality and consistency of printed metal parts.

Overall, this is a strong contribution to the field. The experiments, simulations, and analysis all support the idea that magnetic fields could be a useful tool in improving metal AM processes.

I fully recommend the publication of this paper in its current form.

The authors thank the reviewer for their comments and appreciate that the key message around using and then scaling of the model experiment to real AM practices has benefit to this field.

Reviewer #2: This is a very nice paper reflecting a novel (proposed) solution to AM's challenges. The experiment gives a good basis for both asserting the validity of the model and extending the principle to AM.

We thank the reviewer for their overall summary of the paper and highlighting the benefit of the model experiment.

Since you assert that this technique may be used to reduced grain size and directionality in AM, I do wonder what the microscopy of your experiment looked like - did you see grain refinement?

The experiment is several orders of magnitude larger in length to 'real' AM processes and it therefore not possible to compare grain structures to the model experiment. The experiments were also performed with room temperature liquid metal to observe the flow patterns and no solidification took place, hence no grain structures were observed and so we do not discuss grain refinement in the paper. However, we agree that the benefits TEMHD promises could lead to grain refinement and indeed in the wider literature this has been seen.

The use of magnetic fields to cause grain refinement has been observed in many traditional processes. There is also now experimental evidence showing that the same is true in AM a result of TEMHD flows. It is concluded by many authors that forced convection refines grains in general. Our work focussed on understanding and controlling the thermoelectric flows, which from these papers in the literature we infer will have an influence on grain structures.

We have added references into the manuscript along with a few words describing the grain refinement as a benefit. First to grain refinement in traditional techniques:

“... significant effect on the solidified metal [12, 13, 14] **including beneficial effects like grain refinement [15, 16]**”

Followed by AM specific papers:

“... AM **with grain refinement also observed [17, 18]. Magnetic fields in AM have also been shown to address** various problems such as precisely timed, exact size droplet ejection ...”

In the introduction, "AM is a clean and efficient technology due to minimal waste material ..." This is a controversial statement.

We agree that many current AM processes have not yet reached the level of efficiency as their equivalent, traditional, methods. However, the rapid growth and investment into AM technology seeks to reduce this gap in terms of energy and efficiency. Examples include (and by no means exhaustive), efforts to increase coupling (efficiency) between the laser and powder, recycling of powders and in our case melt flow control.

We have modified this sentence to be:

“AM **has the potential to be** a clean and efficient technology due to minimal waste material”

Please add a few more sentences introducing and explaining the Seebeck (thermoelectric) effect (Page 3, 3rd paragraph).

A more detailed explanation about thermoelectric potential and how it leads to current is added to the text. Text now reads:

“During AM extremely high local thermal gradients are present in the melt pool and nearby solid zone. Seebeck coefficient or absolute thermoelectric power can be different for liquid and solid metals. It is an electron transport property, and it can be discontinuous during phase change. If there is a thermal gradient along the interface, then a voltage difference is also generated along the solid-liquid interface. Thermoelectric currents then circulate at the solid-liquid interface as a result of this voltage difference. The current originates from the Seebeck effect between solid and molten material, and its amplitude is proportional to temperature gradient, electrical conductivity of both materials and differential Seebeck coefficient between solid and liquid states of the metal.”

In discussions on the experiments with the bimetal bowl - further clarify the electric current directionality relative to the seam of the bowl. Unclear in several places in this discussion.

Our results show that with the Steel-Cobalt Bi-Bowl only one half of the bowl generates TE current. We have clarified the direction of the current at the position in the manuscript where the figure showing the current is discussed. The following text has been added when describing the figure:

“The figure shows that the current in the Steel is much smaller (practically zero) compared to Cobalt. There is no current between the Cobalt and the Steel and consequently the current passes along the seam (in the z direction) across the Cobalt – GaIn interface. The current then circulates through the liquid GaIn and back into the Cobalt. With no current in the Steel, there is no circulation between the GaIn and Steel and the current is focussed in the liquid region above the Cobalt half of the bowl.”

Figure 5: It may be helpful to draw the seam in the bi-metal bowl over the figures to further clarify.

We have updated all the Figures include x,y and z on the axis to add clarity on the directions. In Figure 5, the seam has been superimposed on to the results as a dashed line. The following text has been added to the figure caption:

“Seam is highlighted by horizontal dotted line with cobalt being the top part in all figures.”

Page 14-15 and Figures 7 and 8: It is asserted that "there is good agreement across all 3 solutions and the experimental data points." However, the plots do not reflect this well and instead appear that with scaling, the experimental results do not agree with the numerical or analytical model. (Between B/Bc = 1-3 in figure 7 and all experimental points in Figure 8).

We believe the reviewer is referring to the experimental data error bars falling outside of the analytic and numerical predictions. To give some more details, the error bars were calculated by taking an typical experiment an analysing the variation in

measured velocities in the region of maximum velocity. We found the standard deviation of the velocity to be approximately 20% of the mean value. This the standard deviation is presented in the error bars presented in figures 7 and 8. However, this error only represents the ‘measurement’ error, and the true error is much harder to quantify. We are essentially comparing three different data sets (experimental, numerical and analytic) and there inevitably assumptions that arise between the three. For example, the geometry in the numerical model is idealised compared to the experiment, the model lacks a free surface, the temperature boundary conditions in the model are taken from measured experimental temperature data and the amount of liquid metal and acid are exact across all experiments. All of these will influence both the length scale and current density (indirectly through thermal gradient) and ultimately both driving and damping forces.

The focus of this paper is on the distinct difference between flow patterns based on magnetic field orientation that are consistent with predictions. Also, a direct comparison of the model experiment to AM conditions via an analytic solution with all three approaches lie within a single order of magnitude (the experimental data lies closer to a 40% error).

Therefore, our definition of ‘good’ agreement was factoring in both the qualitative flow structure and trends, along with the quantified scaling.

We have modified the paper to highlight that these 20% error bars represent the minimum error, and the true error is likely to be higher:

“The error bars in figures 7 and 8 are 20% of the measured value. This error was estimated by taking a typical experiment and analysing the standard deviation in velocity in a region of maximum velocity. This accounts only for the measurement error, but there are many other factors that are more difficult to quantify and so represents a minimum error.”

All authors have approved the revised manuscript and agree with its submission to JOM.

Imants Kaldre 

23.04.2025

Model experiment for investigation of thermoelectric magnetohydrodynamics in metal additive manufacturing

Imants Kaldre^{1*}, Valdemars Felcis^{1,2}, Ivars Krastins^{1,2}, Peter Soar²,
Catherine Tonry², Andrew Kao²

¹ University of Latvia, Jelgavas Street 3, Riga, LV-1004, Latvia.

² University of Greenwich, Old Royal Naval College, Park Row, London SE10 9LS, UK.

*Corresponding author: imants.kaldre@lu.lv

Abstract: Metal additive manufacturing is a rapidly growing technology revolutionizing many industries, yet wide adoption is limited due to the unreliability and complexity of the process. Scanning strategies, such as hatching, add further complexity to heat transfer and ultimately microstructure growth. Applying external magnetic fields is a promising technique to improve control of melt flow and heat transfer. High local thermal gradients can cause thermoelectric currents to circulate at the solid-liquid interface. When a magnetic field is applied, a Lorentz force drives fluid flow, which can have significant impact on the melt behavior and solidification outcome. In this work we analyze the impact a static magnetic field has on liquid metal flow using a scale model representative of additive manufacturing which allows us to directly observe and measure the thermoelectric magnetohydrodynamic flow. Experiments with bi-metallic bowl, made of two halves with distinctly different thermo-physical properties, provides an analogy to hatching revealing a strong influence on both thermoelectric currents and ultimately the flow. Through an analytic scaling analysis, the results are compared against numerical models spanning orders of magnitude in both length and velocity, providing a correlation between the model experiment and realistic conditions encountered in industry additive manufacturing processes.

INTRODUCTION

Metal additive manufacturing (AM), often referred to as metal 3D printing, unlocks new possibilities to produce complex custom-shaped parts quickly and without large initial investments. Currently 3D printing is a technique with increasing usage in industry with a wide range of applications and sectors. With rapid global market growth, more resources are being invested in the development of new materials and techniques. AM has the potential to be a clean and efficient technology due to minimal waste material and lower energy consumption compared with subtractive manufacturing techniques. During the AM process, a small quantity of metal is melted by a laser or an electric arc, which then rapidly solidifies. It enables the production of parts with increased complexity at near net shape compared to conventional machining and casting. AM is primarily used to produce a small number of individual parts rather than large volume production. AM for various metals is already commercially available (e.g. steel, aluminum, bronze, titanium, copper, and tungsten). Despite the tremendous benefits of AM, it is currently less developed as a technology compared to machining and casting, and when designing a new part usually engineers must consider the method which will be used to manufacture it. Wide use of AM is still limited because of expensive and complicated equipment and raw materials [1]. Even for common

materials such as 316L Stainless Steel and aluminum, high quality powder or wire suitable for 3D printing costs up to ten times the price of cast alloy. This raw material cost also only constitutes about one third of additive manufacturing expenses, while the rest is mostly depreciation of machinery and energy consumption [2]. Significant expenses arise due to the slow printing process, because every step requires melting, solidification and cooling down of a small metal quantity, thus when aiming for higher accuracy, printing time increases [3]. The most popular techniques of metal AM are directed energy deposition (DED) and powder bed fusion (PBF). In the DED process metal is fed as powder or wire and then melted by laser or electric arc, and deposited onto a surface where it solidifies, fusing materials together with the printed part. In the PBF process a thin layer of metal powder is spread over the previous layer and then fused by arc or laser at certain spots. Such processes require high accuracy in both raw material dosing and heating power regulation to avoid local overheating and get the correct size and shape of printed metal element. The printhead or laser is moved by CNC (computer numerical control) stepper motors, typically one for each of the three axes, but in some cases more complicated systems are used allowing various rotations and other degrees of freedom [4].

It is important that every time the small droplet-sized liquid metal melt pool solidifies in the same conditions. The melt pool is molten for a very short time (several milliseconds), and the typical cooling rate in metal AM is between 10^3 and even 10^6 K/s. Heat and mass transfer in the molten state and during solidification have a significant impact on the outcome of the solidification process and subsequently solidified material microstructure and properties. One issue is that heat and mass transfer in this ultra-fast micro scale process is difficult to control because it is mainly defined by material properties and conditions which cannot be readily altered [5]. During AM of complex structures, it is difficult to ensure reliability and repeatability during the whole AM process, as thermal conditions while printing the corners or edges of the printed part can be very different. In this case, on one side of the melt pool there is solid metal, while on the other side there is powder or air, thus the temperature field during solidification can be highly distorted. This may cause oriented dendrite growth and lead to asymmetric morphology and properties of the solidified volume. Several approaches have been used to address these issues, such as adjusting the printing parameters depending on the location of the printed piece and regulating the nozzle parameters, like temperature and material feeding rate. This is done using sensors, video processing, and machine learning methods to predict the optimum set of parameters for each printing step depending on its location. This has solved some of the problems, but still additional melt pool control methods are needed to further unlock AM capabilities and enable the manufacturing of new materials [6,7]. Accuracy and reliability of AM could be improved if behavior of the liquid metal volume and solidification parameters could be better controlled [8, 9, 10].

Aluminum based alloys are one of the most used metals in automotive and aerospace applications, primarily because of their exceptional combination of low density, high specific strength and excellent resistance to corrosion. There are many different aluminum alloys suitable for various additive manufacturing approaches, but because of the high cooling rate only a handful of them are suited for AM. Wire additive manufacturing (WAM) is the fastest additive manufacturing process, allowing it to quickly and reliably produce complex parts which do not require high accuracy or can later be machined to finish. WAM is in principle a welding process where the part is

manufactured by welding layer on layer using electric arc or laser printhead. Specifically high strength aluminum alloys such as 2, 6 and 7 series are difficult to produce by AM due to high internal stresses after solidification, leading to porosity and cracking. There are some exceptions e.g. Scalmalloy which utilizes Scandium (Sc), a rare, high-cost metal additive to avoid cracking via the mechanism of acting as a nucleation center for the solidification. This alloy can resist ultra-high (10^6 K/s) cooling rates, but complex production of powder and low availability of Sc limits the scalability of the application of this material [11].

A promising approach for better melt pool control is using contactless electromagnetic methods, where applied magnetic fields induce forces in the molten metal. There are numerous scientific studies about metallic alloy solidification under various magnetic fields, showing that heat and mass transfer can be modified resulting in a significant effect on the solidified metal [12, 13, 14] including beneficial effects like grain refinement [15, 16]. Magnetohydrodynamics (MHD) studies the various phenomena associated with the interaction between magnetic fields and electrically conducting liquid media. MHD methods for improved control of the liquid metal are recently considered as a promising approach in metal AM with grain refinement also observed [17, 18]. Magnetic fields in AM have also been shown to address various problems such as precisely timed, exact size droplet ejection from the printhead [19] and affect the heat transfer in the melt pool [20].

During AM extremely high local thermal gradients are present in the melt pool and nearby solid zone. Seebeck coefficient or absolute thermoelectric power can be different for liquid and solid metals. It is an electron transport property, and it can be discontinuous during phase change. If there is a thermal gradient along the interface, then a voltage difference is also generated along the solid-liquid interface. Thermoelectric currents then circulate at the solid-liquid interface as a result of this voltage difference. The current originates from the Seebeck effect between solid and molten material, and its amplitude is proportional to temperature gradient, electrical conductivity of both materials and differential Seebeck coefficient between solid and liquid states of the metal. The current density $\mathbf{J}$ is given by Ohm's law

$$\mathbf{J} = \sigma(\mathbf{E} - S\nabla T + \mathbf{u} \times \mathbf{B}) \quad (1)$$

where σ is the electrical conductivity, $\mathbf{E}$ is the electric field, S is the Seebeck coefficient, T is the temperature, $\mathbf{u}$ the fluid velocity and $\mathbf{B}$ the magnetic field. The Seebeck coefficient is an electron property (analogous to P and N type semiconductors) and therefore for many materials it is different for solid and molten states at the melting temperature. The thermoelectric currents can circulate at very small scales, comparable to the melt pool size itself and the current density can reach extremely high magnitude in a small volume, because of the high electric conductivity and temperature gradient. If a magnetic field is applied it creates a Lorentz force, $\mathbf{J} \times \mathbf{B}$, which can drive liquid metal flow from the $\sigma S \nabla T$ term, but also damp the flow from the induced currents ($\sigma \mathbf{u} \times \mathbf{B}$ term). This driving phenomenon is called thermoelectric magnetohydrodynamics (TEMHD), also commonly referred to as thermos-electro-magnetic convection, TEMC [21, 22, 23].

This work aims to quantify the TEMHD role in metal AM by designing and conducting a low-temperature lab-scale model experiment which allows for direct optical observation of the TEMHD generated liquid metal flow. The flow varies with different

applied static magnetic field orientations and strength. Our recent work on similar scale models to quantify this effect demonstrates the possibility to achieve considerable liquid metal velocity by means of TEMHD and electric current injection [24, 25]. Numerical models of this TEMHD case also showed a good agreement to the experiment, thus model experiments can be valuable for prediction of behavior of liquid metal in realistic aluminum alloy processes. TEMHD acts as a volume force, which in real AM processes is present in the small melt pool, typically a few hundred micrometers in diameter. However, even with a moderate magnetic field, on the order of 1 T and within the range of permanent magnets, the thermoelectric force can become dominant, competing with or overcoming other inherent forces such as Marangoni stress and buoyancy. For example, recent experiments at synchrotron radiation facilities indicate that TEMHD can be comparable to strong Marangoni flows (1 m/s) present in the melt pool of laser AM with magnetic field strengths in the range of permanent magnets (0.5 T) [26, 27].

METHODOLOGY

The experimental setup consists of a shallow metallic bowl with an inner diameter of 40 mm and depth of 10 mm at the center. The magnetic field is applied by a permanent magnet assembly, which allows for the field orientation to be changed and a magnitude from 0 to 100 mT [28]. This magnet assembly can create a magnetic field either in transverse or axial directions. The field strength can be adjusted by moving the magnets closer in or further apart. In this work, we consider two bowls, the first is entirely made of Cobalt (Fig. 1a) and the second, a bi-metal bowl, consists of two halves, one half is Cobalt, and the other is Stainless Steel (Fig. 1b). The second case breaks the axial symmetry as Cobalt has a high $S = -24 \mu\text{V/K}$, while S for Stainless Steel is close to $0 \mu\text{V/K}$. Heating is introduced from the bottom of the bowl using an electrically heated copper rod in contact with the bowl. Heat is extracted from the outer edge of the bowl by a water-cooled copper pipe soldered to the side of the bowl. Heating from the bottom allows the free surface to be unobscured for observations. The overall scheme of the experiment is shown in Fig. 1c. The temperature is measured by several thermocouples, which are placed outside the bowl or in the melt pool in various places. This temperature data is then used to provide boundary conditions for the numerical simulations.

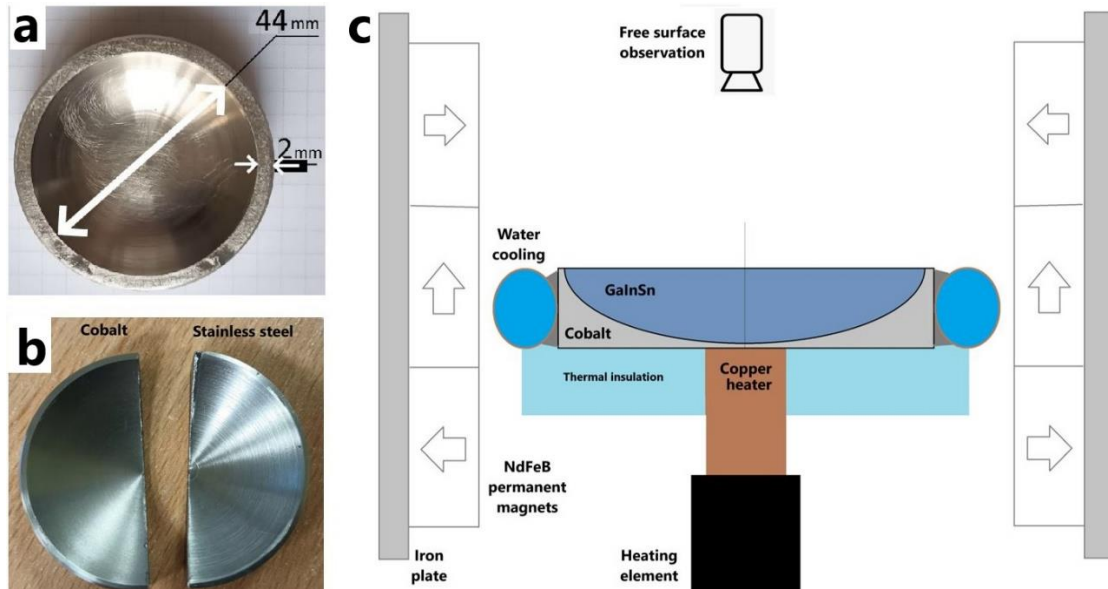


Figure 1. Experimental setup: a) Cobalt bowl; b) Bi-metal Cobalt-Stainless Steel bowl; c) Schematic cross section of the experimental setup (not to scale).

The liquid GaInSn free surface is covered with a thin layer of HCl aqueous solution (3-5 %) to break the oxide film and create a protective layer. The metal surface flow pattern is observed by a digital camera, recording 60 frames per second videos. Oxide particles and small bubbles from the reaction with the acid conveniently serve as tracer particles for the liquid metal surface flow visualization and video processing to obtain the surface velocity distribution. The flow is measured from the videos by tracing the particles and bubbles floating on the surface using the Trackpy Python package [29], which allows mapping the surface velocity distribution. Particles are automatically selected by particle size and brightness. Each particle is tracked frame by frame. To create particle trajectories, the built-in predictor function is used that estimates the instantaneous velocities of a group of nearby particles. Obtained trajectories can then be processed to calculate point velocities at measured particle positions by using distance traveled in a single frame and camera framerate. Across a single two minute measurement video around a million particles can be tracked across all frames. Therefore, distance-weighted averaging of velocities was used to create a structured grid of velocities with a resolution of 0.2 mm to eliminate most particle tracking errors and allow for simpler post processing of the data. The averaging procedure is to take a particular point on the chosen grid, then taking points in a 1.41 mm circle around it and taking an average weighted by the distance to the chosen grid point. A high-speed camera is positioned directly above the melt pool, recording the top surface showing the flow through oxides and bubbles on the surface. Fig. 2 shows a typical example of experimental data, where Fig. 2a shows an image of the raw data and Fig. 2b shows the particles detected by tracking algorithm. Using successive frames streamlines shown in Fig. 2c and velocity contours can be reconstructed and compared to the numerical simulations. Due to reflections of the light on the curved surface saturating the optical imaging, in some regions particles could not be tracked and have been blanked (white) in the results sections.

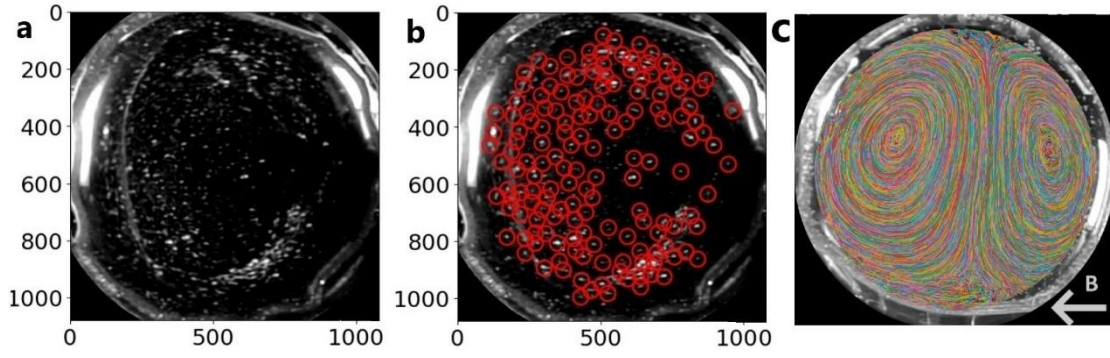


Figure. 2. Video processing and particle tracking: a) Video frame with liquid GaInSn surface, b) Selected particles which are tracked, c) Particle trajectories ($B=75$ mT).

To better understand the physical processes in the melt pool, numerical simulations are conducted using COMSOL Multiphysics 6.0. The temperature distribution is simulated using experimental measurements as boundary conditions. Thermoelectric currents are calculated from the temperature field using Ohm's law (Eq. 1). The Lorentz force, $\mathbf{J} \times \mathbf{B}$, is then calculated by adding a source term in the steady-state Navier-Stokes equation given by

$$\rho \mathbf{u}(\nabla \mathbf{u}) = -\nabla p + \mu \Delta \mathbf{u} + \sigma(\mathbf{E} + \mathbf{u} \times \mathbf{B} - S \nabla T) \times \mathbf{B} \quad (2)$$

where ρ is the density, p the pressure and μ the dynamic viscosity. The force $\sigma \mathbf{u} \times \mathbf{B} \times \mathbf{B}$ is the electromagnetic damping force, common to MHD problems.

Other effects considered are Marangoni surface force which originates from temperature dependence in the surface tension and natural convection due to the density having a temperature dependence. While in real AM processes Marangoni is typically the primary driver, in this model experiment, due to the large length scales, these were found to be at least order of magnitude smaller than Lorentz forces considered and thus neglected in further calculations. Physical properties of the materials used in the experiments, numerical models, and analytical calculations are given in Table 1. For comparison, liquid and solid aluminum properties at the melting temperature are included in the table.

Table 1. Physical properties of the materials used in experiments and numerical models.

Property	Symbol	Cobalt	GaInSn [30]	Stainless Steel	Al (at m. p.)	Liquid Al (at m. p.)
Electric conductivity (MS/m)	σ	16	3.3	1.3	6	4
Density (kg/m^3)	ρ	8900	6360	7950	2700	2400
Thermal conductivity ($\text{W/m}\cdot\text{K}$)	λ	100	16	14	185	89
Heat capacity ($\text{J/kg}\cdot\text{K}$)	c	468	371	482	903	1127
Seebeck coefficient ($\mu\text{V/K}$)	S	-24	-0.4	0	0	-1

Dynamic viscosity (mPa·s)	μ	-	3	-	-	1
Surface tension (N/m)	γ	-	0.6	-	-	0.8

RESULTS AND ANALYSIS

Cobalt Bowl

Heat flux is primarily in the radial direction, extending from the central hot spot at the bottom to the water-cooled edge of the bowl, creating a radially symmetric temperature distribution. If the differential Seebeck coefficient between solid and liquid metals is non-zero, then the thermoelectric current will originate at the interface forming an axially symmetric path, in this case from the center to the side through the liquid metal and return through the solid bowl. The temperature field in the experiment is determined based on thermocouple measurements at certain points inside and outside of the melt pool. The typical temperature difference during experiment between the bottom of the melt pool and outer edge is around 10 °C, thus in the model experiment a typical thermal gradient is 500 K/m. Using these measured values as boundary conditions, the numerically calculated temperature field and thermoelectric current distribution in Cobalt bowl are shown in Fig. 3a and 3b.

While heating from the bottom gives a different temperature field compared to AM processes that are heated from the top, the resultant thermoelectric currents are quite similar. The current emanates normal to the base of the bowl in the axial direction, circulating into a radial current through the liquid and then returning through the Cobalt bowl (Fig. 3b). Such behavior is also predicted in direct models of the AM process [22].

When an axial magnetic field is applied, the field only interacts with the radial component of $\mathbf{J}$ and the Lorentz force becomes angular, driving a rotational flow (Fig. 3(c-e)). An axial field retains the symmetry of the system, however in the case when a transverse magnetic field is applied, this symmetry is broken. The magnetic field primarily interacts with the axial current generating a force normal to the field and along the bowl. The corresponding flow traverses the bowl, but due to the geometry leads to a stagnation point at the edge. As the force is concentrated in the center, to preserve continuity, the flow reverses direction forming a pair of vortices (Fig. 3 (f-h)). For the two magnetic field orientations an excellent agreement is found both in terms of the magnitude of the flow and the direction of flow. The results are also consistent in terms of the number of vortices and directions with simulations of the AM process [22]. In the transverse case one of the vortices is slightly larger than the other, which can be attributed to the difficulty of applying a perfectly centered heat source. Slight deviations from the middle skew the vortices, while in the axial case this effect is much smaller. The results show that even with only a 10 K temperature difference between the bottom and the side of the melt pool can drive TE current of 10^5 A/m² and with modest magnetic field of 15 mT TEMHD velocities can reach up to 120 mm/s with axial magnetic field and 50 mm/s with transverse field.

current in the Steel is much smaller (practically zero) compared to Cobalt. There is no current between the Cobalt and the Steel and consequently the current passes along the seam (in the z direction) across the Cobalt – GaIn interface. The current then circulates through the liquid GaIn and back into the Cobalt. With no current in the Steel, there is no circulation between the GaIn and Steel and the current is focussed in the liquid region above the Cobalt half of the bowl. Consequently, when a magnetic field is applied the Lorentz forces are also concentrated in this region. Figs. 4(c-e) show the Lorentz force for each orientation of the magnetic field. Fig. 4d for the axial field and Fig 4e for the field aligned along the seam particularly highlight how the Lorentz force is focused in the Cobalt region.

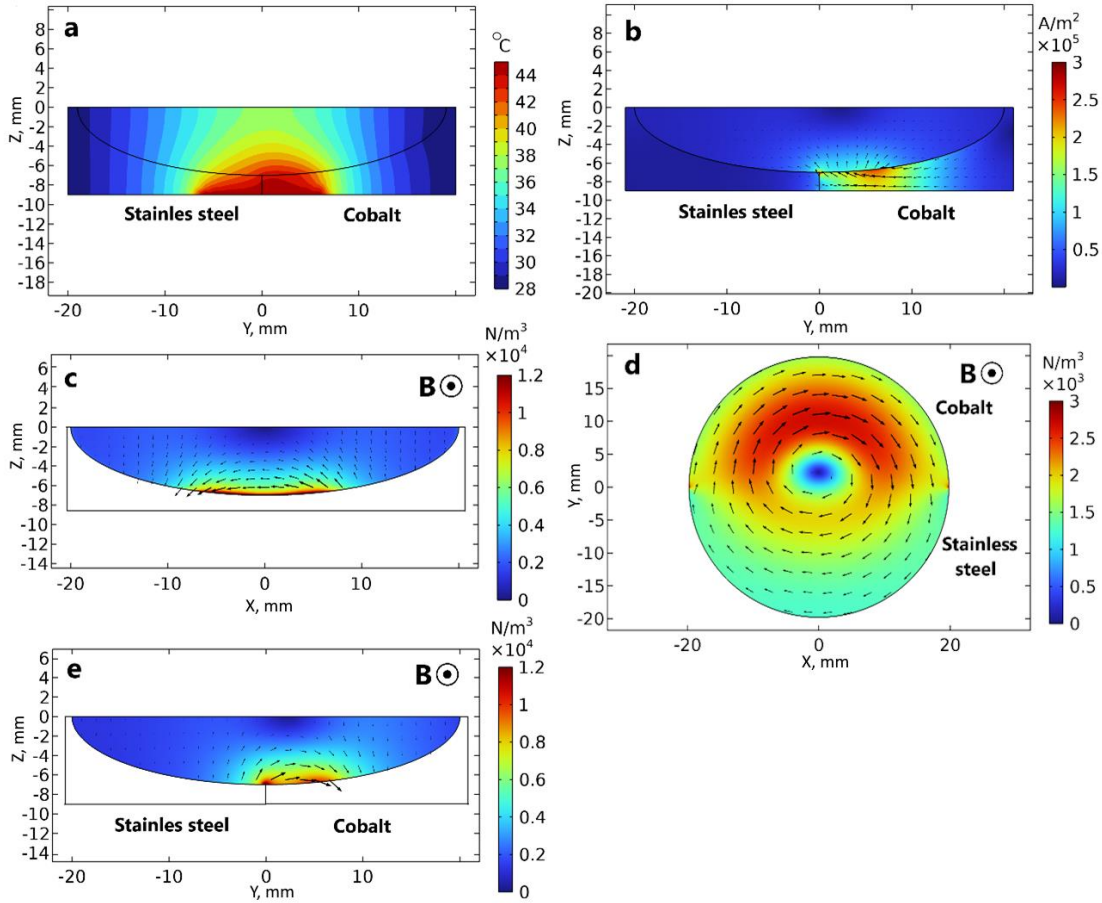


Figure 4. Numerical simulation of bi-metal bowl: a) Thermal field, b) Current distribution. Lorentz force distribution with $B=15$ mT: c) Magnetic field across the seam, d) Axial magnetic field, e) Magnetic field along the seam.

Due to the skewing of the thermoelectric currents, the symmetry of the system is further broken compared to the pure Cobalt bowl. There are therefore three magnetic field orientations to consider (in order of breaking symmetry): an axial field, a transverse field across the joint and a transverse field along the joint. Fig 5. shows all these cases and comparison between numerical simulations and experimental observations.

With an axial field, the Lorentz force is still predominantly angular, but with the highest magnitudes in the Cobalt region. The flow then accelerates in this region and to preserve continuity a rotational flow still forms across the entire bowl, but the highest velocities are now in the Cobalt region (Fig. 5 (a-c)). Applying a transverse magnetic field

along the joint line of the bi-metal bowl preserves the symmetry plane across the joint line. Although the Lorentz force is focused in the Cobalt region, it drives flow along this symmetry plane, and like the pure Cobalt bowl case, a stagnation point form on the edge and combined with continuity again leads to the formation of two symmetric vortices (Fig. 5(d-f)). The symmetry of the system can be further broken by applying a transverse magnetic field across the bi-metal joint. The numerical modelling suggests that this should lead to a more complex system of vortices with the largest vortex in the Cobalt region, followed by a smaller one in the Stainless Steel region (Fig. 5(g)). However, the experimental results are similar to that of the axial case (Fig. 5(h-i)), but a key difference is that the orientation of the flow is reversed and the mechanism for the rotational flow is somewhat different. In the axial case $\mathbf{J} \times \mathbf{B} \approx J_r B_z \hat{\theta}$, where J_r is the radial current and is positive and B_z is the axial field and is also positive creating a positive angular ($\hat{\theta}$) force (clockwise). However, for this transverse case $\mathbf{J} \times \mathbf{B} \approx -J_z B_y \hat{x}$, where J_z and B_y are positive, but the resultant force is negative in $\hat{x}$. Due to the skewed currents this force is off center compared to the perpendicular transverse magnetic field case and consequently drives the apparent angular flow in a counter-clockwise fashion. The numerical results also represent an idealized scenario, but as seen in the transverse pure Cobalt bowl case, the system is sensitive to small asymmetries. The numerical results show that there is a dominant vortex and it is highly likely that this has expanded further to occupy the entire surface.

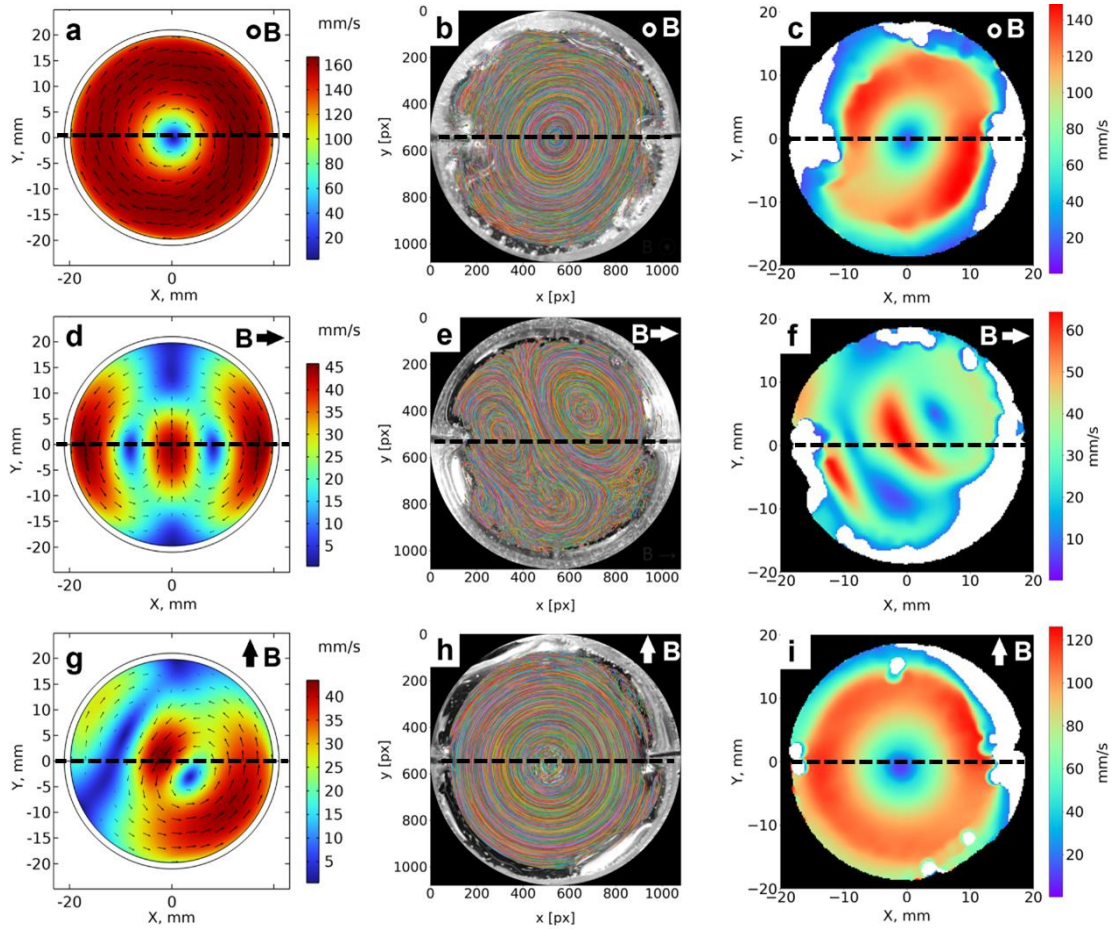


Figure 5. TEMHD velocity in bi-metal bowl. (a-c) Axial magnetic field $B=20$ mT: a) Numerical simulation, b) Particle traces, c) Velocity contour. (d-f) Transverse magnetic field along the seam $B=25$ mT. d) Numerical simulation, e) Particle traces,

f) Velocity contour. Transverse magnetic field across the seam $B=20$ mT: g) Numerical simulation, h) Particle traces, i) Velocity contour. Seam is highlighted by horizontal dotted line with cobalt being the top part in all figures.

Application to AM Process

TEMHD in actual AM arises from large volume force, which is present in small melt pool typically of few hundred micrometers. Even with moderate magnetic fields, thermoelectric force can become a dominant force acting on the liquid metal. To assess the forces in real AM case the same model is calculated for Aluminum melt pool 0.2 mm across using the properties from Table 1. Numerical simulation results are shown in Figure 6. Figs. 6a and b show the temperature field and the thermoelectric current distribution in a realistic Aluminum AM case. In this case the temperature gradient is on the order of magnitude of 10^7 K/m and thermoelectric currents are as high as 5×10^7 A/mm². The corresponding velocity distribution at the liquid metal surface at 1.5 T are given in Figs 6c and 6d for the axial and transverse magnetic fields respectively, and show similar characteristics to the pure Cobalt case given in Fig 3, except the length scales are much smaller and velocities much higher. Applying a very high magnetic field of 5 T is shown in Figs 6e and 6f for the axial and transverse cases respectively, where through the action of the electromagnetic damping force the flow field is modified. In both cases the velocity magnitude is reduced, while in the transverse case the flow morphology is also somewhat modified with the central maximum being damped more severely compared to the edges of the melt pool.

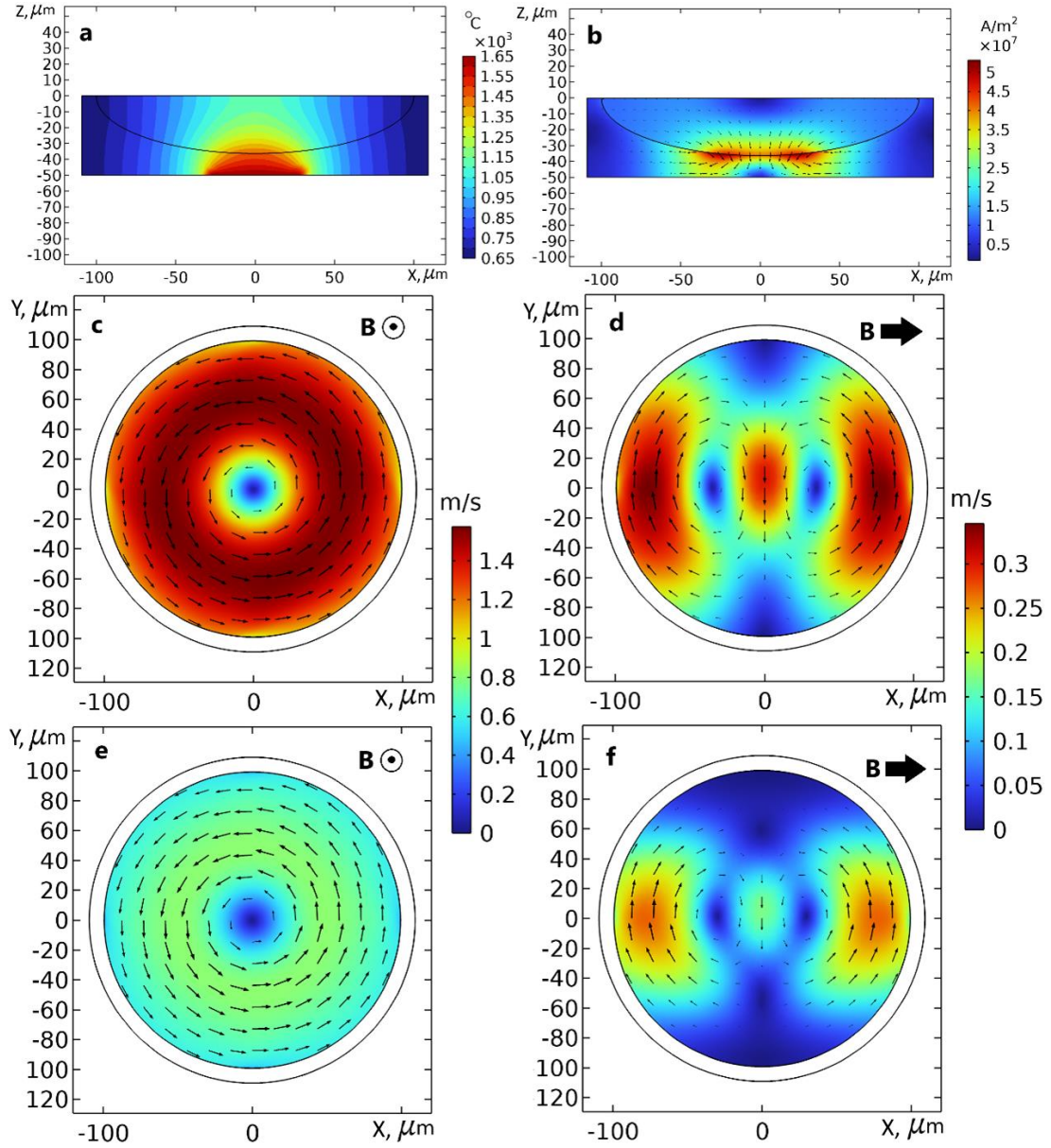


Figure 6. Numerical simulation of TEMHD velocity in Aluminum melt pool: a) Temperature field, b) Thermoelectric current distribution. TEMHD surface velocities: c) Axial magnetic field of 1.5 T, d) Transverse magnetic field of 1.5 T, e) Axial magnetic field of 5 T, f) Transverse magnetic field of 5 T.

To directly compare the bowl experiments to more industry relevant processes such as AM, where length scales and magnetic field intensities are contrastingly different, the following derives an analytical approach informed by numerical simulations. Taking the steady-state Navier-Stokes equation (Eq. 2) and neglecting the inertial term leads to

$$-\nabla p + \mu \nabla^2 \mathbf{u} + \sigma \mathbf{E} \times \mathbf{B} + \sigma \mathbf{u} \times \mathbf{B} \times \mathbf{B} - \sigma S \nabla T \times \mathbf{B} = \mathbf{0}. \quad (3)$$

The electric field $\mathbf{E}$ acts to preserve continuity of charge ($\nabla \cdot \mathbf{J} = 0$) and in this context, we assume that it acts against the thermoelectric field such that $\mathbf{E} = C_E S \nabla T$, where $0 < C_E \leq 1$. The case when $C_E = 1$ represents a situation where the electric field perfectly balances the thermoelectric field and no thermoelectric current forms, such a

case can exist when the medium is homogenous. Conversely, $C_E \neq 0$ if $|S|$, $|\nabla T|$ and σ are all greater than zero, as the thermoelectric field, $S\nabla T$, (or more specifically the thermal gradient) cannot form closed paths. Through a similar argument, ∇p serves to preserve continuity of mass ($\nabla \cdot \mathbf{u} = 0$) and again, in this context, will act against the driving thermoelectric Lorentz force, yielding the assumption $-\nabla p = C_p \sigma S \nabla T \times \mathbf{B}$. Then by approximating $S \nabla T \times \mathbf{B} = S |\nabla T| |\mathbf{B}|$, the proportionality constants can be combined with the thermoelectric term into $C_0 = 1 - C_E - C_p$, where $0 \leq C_0 \leq 1$. The other terms can be approximated as $\mu \nabla^2 \mathbf{u} = \mu \frac{|\mathbf{u}|}{L^2}$, and $\sigma \mathbf{u} \times \mathbf{B} \times \mathbf{B} = \sigma |\mathbf{u}| |\mathbf{B}|^2$, where L is the characteristic length. This leads to the solution for the velocity as a function of the magnetic field,

$$|\mathbf{u}| = \frac{C_0 \sigma S |\nabla T| |\mathbf{B}|}{\left(\sigma |\mathbf{B}|^2 + \frac{\mu}{L^2}\right)} \quad (4)$$

The critical magnetic field, $|\mathbf{B}_c|$, can be determined from Eq. 4 when $\frac{\partial |\mathbf{u}|}{\partial |\mathbf{B}|} = 0$. The final expression for that is $\sigma |\mathbf{B}|^2 = \frac{\mu}{L^2}$ which is the solution when the Hartmann number is 1,

$$|\mathbf{B}_c| L \left(\frac{\sigma}{\mu}\right)^{\frac{1}{2}} = \text{Ha} = 1. \quad (5)$$

For a given viscosity and electrical conductivity, this condition is satisfied by the product of the critical magnetic field and characteristic length scale. In both the bowl experiment and AM processes defining the characteristic length scale is not straightforward, it represents the viscous boundary layer, but in turn this could be related to the dimensions of the melt pool (e.g. width or depth) or an associated length scale of the current. In this solution we instead define the critical magnetic field from the numerical solutions, which in turn yields values for the length scale. For the bowl, $|\mathbf{B}_c| = 0.03$ T and $L = 1.05$ mm, and for the Aluminum AM process, $|\mathbf{B}_c| = 1.5$ T and $L = 21$ μm , where these length scales are at least 6 times smaller than the depth, but appear to correspond to the length scales of the thermoelectric currents into the melt. In general, this is also related to the morphology of the melt pool but can be considered constant for a given morphology. Substituting $L = \frac{1}{|\mathbf{B}_c|} \left(\frac{\mu}{\sigma}\right)^{\frac{1}{2}}$ back into the velocity solution gives

$$|\mathbf{u}| = \frac{C_0 S |\nabla T| |\mathbf{B}|}{(|\mathbf{B}|^2 + |\mathbf{B}_c|^2)} \quad (6)$$

and at the critical magnetic field, $|\mathbf{B}| = |\mathbf{B}_c|$, gives the critical velocity, $|\mathbf{u}_c|$, where

$$|\mathbf{u}_c| = \frac{C_0 S |\nabla T|}{2 |\mathbf{B}_c|} \quad (7)$$

Taking the ratio of the velocity, Eq. 6, to the critical velocity, Eq. 7, gives

$$\frac{|\mathbf{u}|}{|\mathbf{u}_c|} = \frac{2 |\mathbf{B}_c|^2}{(|\mathbf{B}|^2 + |\mathbf{B}_c|^2)} \frac{|\mathbf{B}|}{|\mathbf{B}_c|}. \quad (8)$$

This form gives a direct way to compare the disparate cases of the bowl experiment and the AM process. When $|\mathbf{B}| = |\mathbf{B}_c|$, the right-hand side becomes unity as this represents

the solution of $|\mathbf{u}| = |\mathbf{u}_c|$. Interesting examples of this solution are when the magnetic field is either half the critical field, $|\mathbf{B}| = |\mathbf{B}_c|/2$ or double $|\mathbf{B}| = 2|\mathbf{B}_c|$, both giving $|\mathbf{u}|/|\mathbf{u}_c| = 4/5 = 0.8$. With reference to the Aluminum AM case from Figure 6 and related experiments, although the critical field may be in the region of 1.5 T, applying a magnetic field of 0.5 T e.g. ref [31], a third of the critical field can still drive a significant flow of 60% compared to the critical field. However, as shown in Figure 6, even with a magnetic field potentially an order of magnitude larger (5 T), TEMHD would still be over 50% of its critical value and therefore for most practical applications it would be near impossible to damp out TEMHD even with superconducting magnets.

In essence this solution scales both the velocity axis by $|\mathbf{u}_c|$ and magnetic field axis by $|\mathbf{B}_c|$, where the critical point is at (1,1). This same scaling can be applied to both the bowl (numerical model and experimental data) and AM process modelling, allowing for a direct comparison, where each case is scaled against its own critical field and critical velocity. In the purely analytic case C_0 vanishes when scaling against the critical velocity, but to scale the numerical simulations and experimental data, C_0 is captured from the predicted critical velocity and critical magnetic field i.e. $C_0 = 2|\mathbf{u}_c||\mathbf{B}_c|/S|\nabla T|$.

Figures 7 and 8 show a comparison for the bowl, the AM process and the analytic solution for an axial magnetic field (Figure 7) and a transverse magnetic field (Figure 8). The error bars in figures 7 and 8 are 20% of the measured value. This error was estimated by taking a typical experiment and analysing the standard deviation in velocity in a region of maximum velocity. This accounts only for the measurement error, but there are many other factors that are more difficult to quantify and so represents a minimum error. However, in both cases there is a good agreement across all three solutions and the experimental data points.

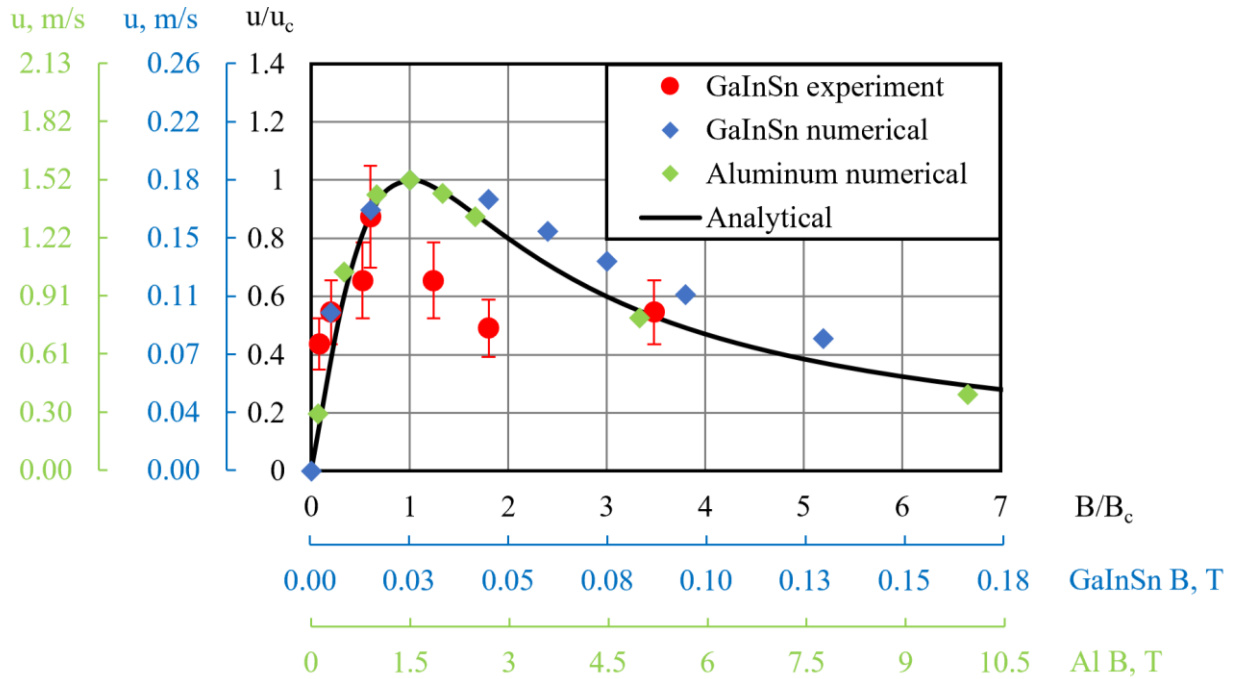


Figure 7. Comparison between the experiment, numerical model and analytical solution for the axial magnetic field case.

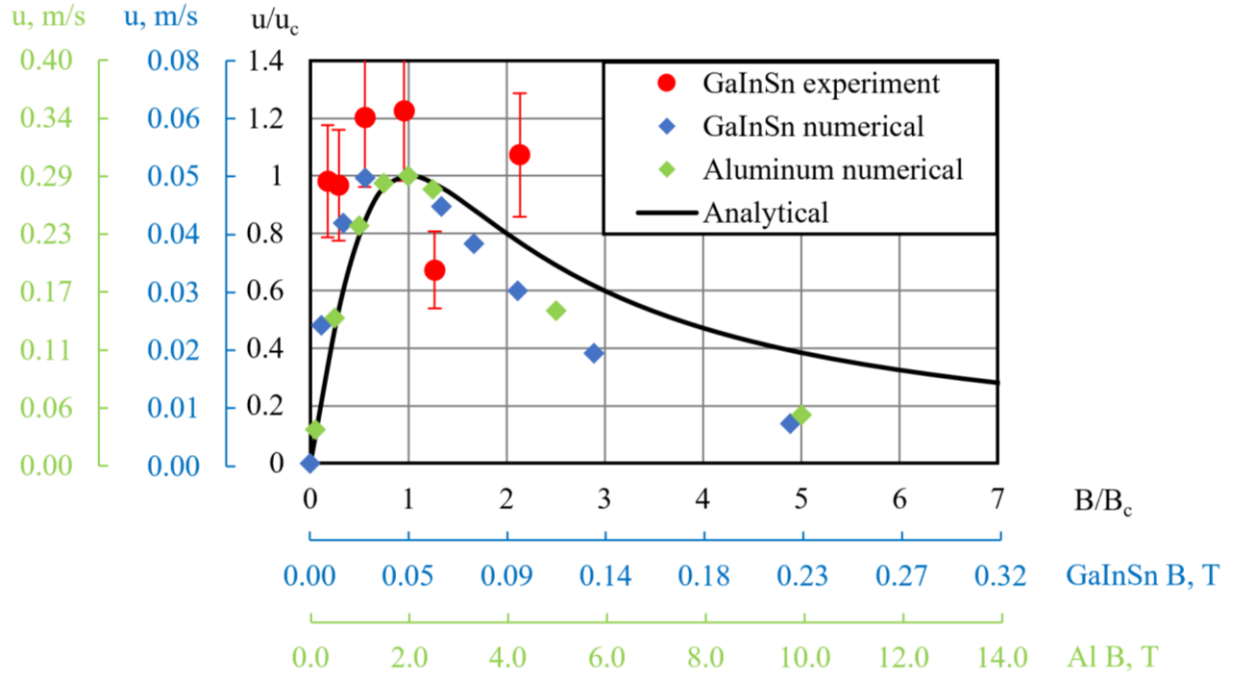


Figure 8. Comparison between the experiment, numerical model and analytical solution for the transverse magnetic field case.

This correlation allows for changes in the bowl experiment to be directly mapped back to an AM process, factoring in changes to length scales, magnetic field intensity, flow velocity and material properties, some that conveniently vanish through scaling. There are essentially three unknowns L , C_E and C_p . In many cases C_E may be estimated by comparing an axial magnetic field to a transverse magnetic field. In an axial case, if the flow is purely angular, a pressure gradient cannot form along the streamlines and $C_p = 0$ and assuming C_E is unchanged between magnetic field orientations yields an additional constraint. Calibration of the analytic solution against bowl experiments and modelling may always be necessary to accurately estimate L and C_E , both of which are dependent on the morphology of the melt pool. However, this approach allows us to explore geometries that are more closely related to the AM process, such as ellipsoid or ‘teardrop’ shapes that occur due to the scanning process via an experiment that can be easily conducted in the lab, e.g. optical measurements with low magnetic fields and using room temperature materials.

CONCLUSION

A scale model experiment accompanied by numerical simulations has been used to study the thermoelectric magnetohydrodynamic phenomena in metal additive manufacturing. A parametric study of magnetic field orientation and magnitude (ranging from 2 mT to 100 mT) for both the Cobalt bowl and the bi-metal bowl was conducted. In the Cobalt bowl, due to the axis symmetry there are only two orientations, axial and transverse, while in the bi-metal bowl there are three orientations, axial, transverse along the bi-metal surface and transverse perpendicular to the bi-metal surface. A good agreement was found between experiments, numerical models and previous similar research with TEMHD flow.

The bi-metal bowl model replicates the case when there are different media at both sides of the melt pool causing asymmetric heat flux and melting. In this case TEMHD flow is more complex and is very different with different magnetic field orientations. The scale model allows us to verify numerical simulations and improve the understanding of TEMHD flow formation and pattern which can be expected during additive manufacturing.

A scaling analysis suggests that the TEMHD effect can be significant in metal additive manufacturing under moderate magnetic field starting from 0.1 T even if differential Seebeck coefficient between solid and liquid phases is as low as 1 $\mu\text{V/K}$. In a small melt pool with extremely high thermal gradient, which occurs during AM, in many cases TEMHD can be the dominant flow even with low magnetic fields. Understanding flows induced in the liquid phase by the applied magnetic field is critical to developing an additional approach to better control liquid metal flow in the melt pool. This could then be used to improve the accuracy of the metal AM for materials and methods that can exploit the TEMHD phenomenon.

These results highlight the intimate coupling between printing strategies of complex geometries and the magnetic field. Processes such as hatching, printing corners, overhangs etc. will all significantly affect the local material properties, thermal field and ultimately thermoelectric currents. These results show that by selecting different orientations of the magnetic field, various complex flows can be generated. In industrial applications, flow can be used to improve print quality and therefore such a control paves the way for a magnetic field strategy to be intimately coupled with scan strategy.

ACKNOWLEDGEMENTS

This work is supported by the Royal Society International Exchange (IES\R2\222050), UK-Latvian Collaboration on Thermoelectric Control of Additive Manufacturing (UKLatTE-AM), the UK Engineering Physical Sciences Research Council “Tailored Microstructures via Thermoelectric-Magnetohydrodynamics for Additive Manufacturing (TEAM)” (EP/W032147/1) and the University of Greenwich “Multi-scale Multi-disciplinary Modelling for Impact” program (M³4Impact) funded by Research England. The authors are grateful for the financial support to University of Latvia development program with big impact project “Improved control of metal 3D printing by thermoelectric magnetohydrodynamics”.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

REFERENCES

1. K. Raghavendra Pai, Vijeesh Vijayan, K. Narayan Prabhu, *Materials today: Proceedings* (2024). <https://doi.org/10.1016/j.matpr.2024.05.008>
2. R.E. Laureijs, J.B. Roca, S.P. Narra, C. Montgomery, J.L. Beuth, E.R. Fuchs, J. *Manuf. Sci. Eng*, 139(8): 081010 (2017). <https://doi.org/10.1115/1.4035420>
3. N.D. Dejene, H.G. Lemu, *Metals*, 13(2), 424 (2023). <https://doi.org/10.3390/met13020424>

4. W. Ji, R. Zhou, P. Vivegananathan, M. S. Wu, H. Gao, K. Zhou, *Progress in Materials Science*, 140, 101194 (2023).
<https://doi.org/10.1016/j.pmatsci.2023.101194>
5. J. Wang, R. Zhu, Y. Liu, L. Zhang, *Advanced Powder Materials*, 2(4), 1000137 (2023). <https://doi.org/10.1016/j.apmate.2023.100137>
6. C. Liu, Y. Zhang, N. Banthia, *Additive Manufacturing*, 71, 103606 (2023).
<https://doi.org/10.1016/j.addma.2023.103606>
7. D.R. Gunasegaram, A.S. Barnard, M.J. Matthews, B.H. Jared, A.M. Andreaco, K. Bartsch, A.B. Murphy, *Additive Manufacturing*, 81, 104013(2024).
<https://doi.org/10.1016/j.addma.2024.104013>
8. A.T. Nesma, M. Simonelli, L. Parry, I. Ashcroft, C. Tuck, R. Hague, *Progress in Materials Science*, 106, 100578 (2019).
<https://doi.org/10.1016/j.pmatsci.2019.100578>
9. N.T. Aboulkhair, N.M. Everitt, I. Ashcroft, C. Tuck, *Additive Manufacturing*, 1–4, 77–86 (2014). <https://doi.org/10.1016/j.addma.2014.08.001>
10. R. Montanari, A. Palombi, M. Richetta, A. Varone. 2023, *Metals*, 13 (4), 716 (2023). <https://doi.org/10.3390/met13040716>
11. J.H. Martin, B.D. Yahata, J.M. Hundley, J.A. Mayer, T.A. Schaedler, T.M. Pollock, *Nature*, 549 (7672), 365–369 (2017). [10.1038/nature23894](https://doi.org/10.1038/nature23894)
12. I. Kaldre, Y. Fautrelle, J. Etay, A. Bojarevics, L. Buligins, *Journal of Alloys and Compounds*, 571, 50–55 (2013). <https://doi.org/10.1016/j.jallcom.2013.03.211>
13. C. Zeng, J. Xue, Y. Jia, S. Luo, F. Huang, X. Liu, Y. Du, *Journal of Manufacturing Processes*, 131, 920–946 (2024).
<https://doi.org/10.1016/j.jmapro.2024.09.078>
14. I. Kaldre, Y. Fautrelle, J. Etay, A. Bojarevics, L. Buligins, *Journal of Crystal Growth*, 402, 230–233 (2014). <https://doi.org/10.1016/j.jcrysgro.2014.06.029>
15. T. Campanella, C. Charbon, M. Rappaz, *Metallurgical and Materials Transactions A*, 35(10), 3201–3210 (2004). https://doi.org/10.1007/978-3-319-48166-1_18
16. M. Milgrāvis, I. Krastiņš, I. Kaldre, M. Kalvāns, A. Bojarevičs, T. Beinerts, *Crystals*, 13(2), 259 (2023). <https://doi.org/10.3390/cryst13020259>
17. D. Du, L. Wang, A. Dong, W. Yan, G. Zhu, B. Sun, *International Journal of Machine Tools and Manufacture*, 183, 103965 (2022).
<https://doi.org/10.1016/j.ijmachtools.2022.103965>
18. R.P. Silva, R. Soares, R. Neto, A. Reis, R. Paiva, R. Madureira, J. Silva, *Materials*, 15(6), 2038 (2022). <https://doi.org/10.3390/ma15062038>
19. N. Gilani, N.T. Aboulkhair, M. Simonelli, M. East, I. Ashcroft, R.J.M. Hague, *Additive Manufacturing*, 48(B), 102402 (2021).
<https://doi.org/10.1016/j.addma.2021.1024>
20. P. Kumar, S. Malik, E. Toyserkani, and M. B. Khamesee, *Micromachines*, 13(4), 585 (2022). <https://doi.org/10.3390/mi13040585>
21. X. Fan, T.G. Fleming, D.T. Rees, Y. Huang, S. Marussi, C. L. Leung, R.C. Atwood, A. Kao, P.D. Lee, *Additive Manufacturing*, 71, 103587 (2023).
<https://doi.org/10.1016/j.addma.2023.103587>
22. A. Kao, T. Gan, C. Tonry, I. Krastins, K. Pericleous. *Phil. Trans. R. Soc.* 378, 2171 (2020). <https://doi.org/10.1098/rsta.2019.0249>
23. I. Kaldre, Y. Fautrelle, J. Etay, A. Bojarevics and L. Buligins, *Magnetohydrodynamics*, 46(4), 371–380 (2010). <http://doi.org/10.22364/mhd>

24. I. Kaldre, C. Wang, R. Baranovskis, *Magnetohydrodynamics*, 55(4), 469-474 (2019). <http://doi.org/10.22364/mhd>
25. I. Kaldre and V. Felcis, *Magnetohydrodynamics*, 59(3/4), 357-364 (2023). <http://doi.org/10.22364/mhd>
26. A. Kao, C. Tonry, P. Soar, I. Krastins, X. Fan, P.D. Lee, K. Pericleous, *IOP Conf. Ser.: Mater. Sci. Eng*, 1281, 012022 (2023). 10.1088/1757-899X/1281/1/012022
27. X. Fan, T.G. Flemming, S.J. Clark, K. Fezzaa, A.C.M. Getley, S. Marussi, H. Wang, C.L.A. Leung, A. Kao, P.D. Lee, *Science* 387,864-869(2025). <http://doi.org/10.1126/science.ad08554>
28. I. Kaldre, A. Bojarevičs, I. Grants, T. Beinerts, M. Kalvāns, M. Milgrāvis, *Acta Materialia*, 118, 253-259 (2016). <https://doi.org/10.1016/j.actamat.2016.07.045>
29. <https://soft-matter.github.io/trackpy/dev/> (Accessed February 17, 2025) .
30. Yu. Plevachuk, V. Sklyarchuk, S. Eckert, et.al, *Journal of Chemical & Engineering Data* 59(3), 757-763 (2014). [10.1021/je400882q](https://doi.org/10.1021/je400882q)
31. X. Li, Z. Ren, Y. Fautrelle, *Acta Materialia*, 55(11), 3803–3813 (2007). <https://doi.org/10.1016/j.actamat.2007.02.031>

Figure 1

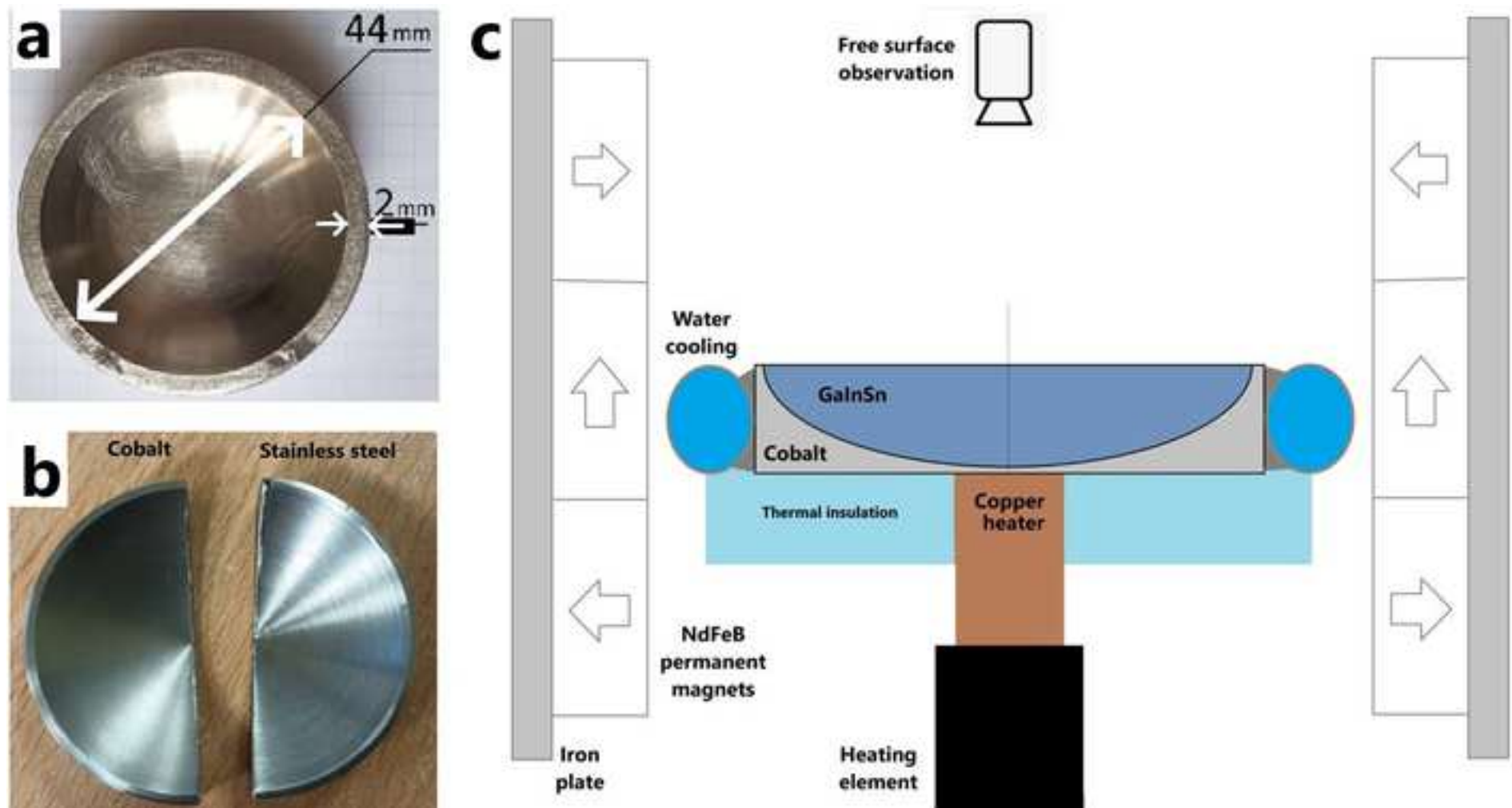


Figure 2

[Click here to access/download;Figure;Figure 2.jpg](#) 

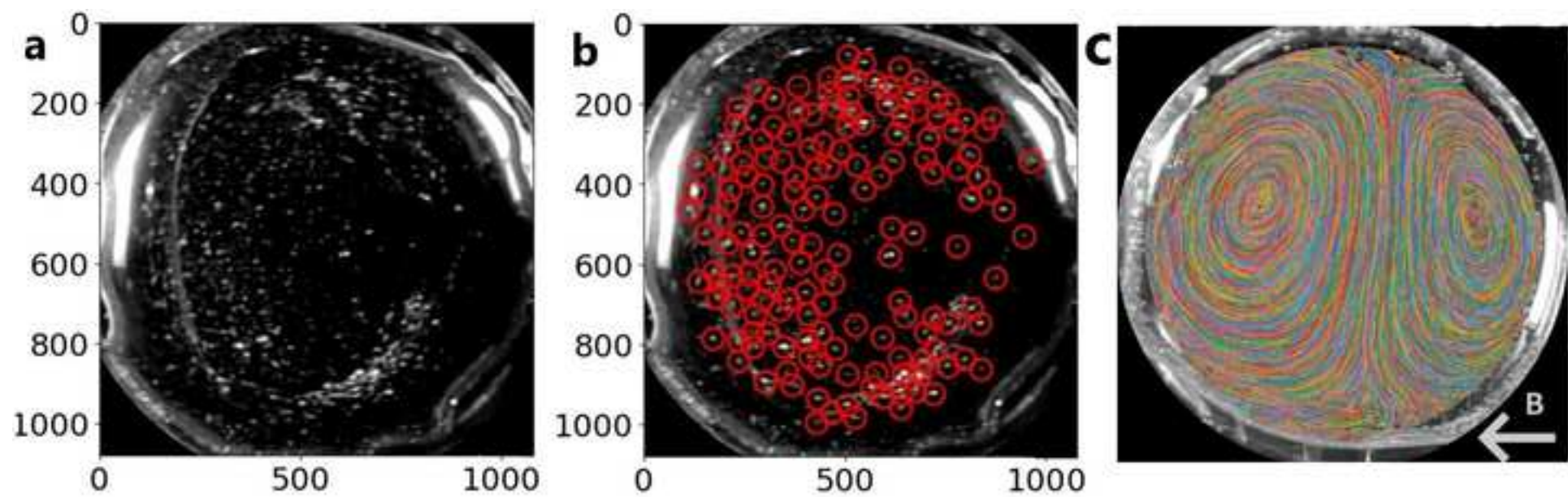


Figure 3

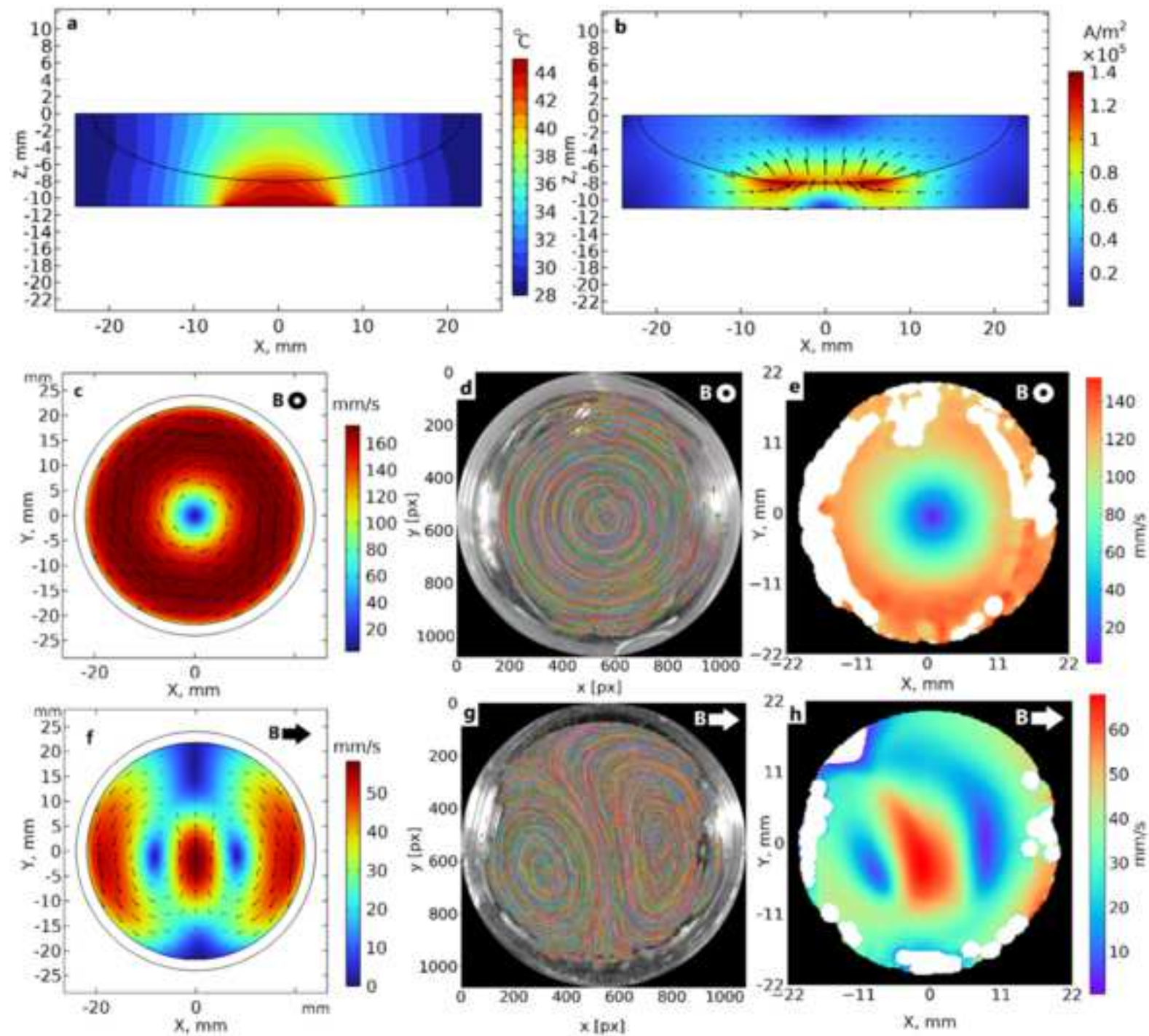


Figure 4

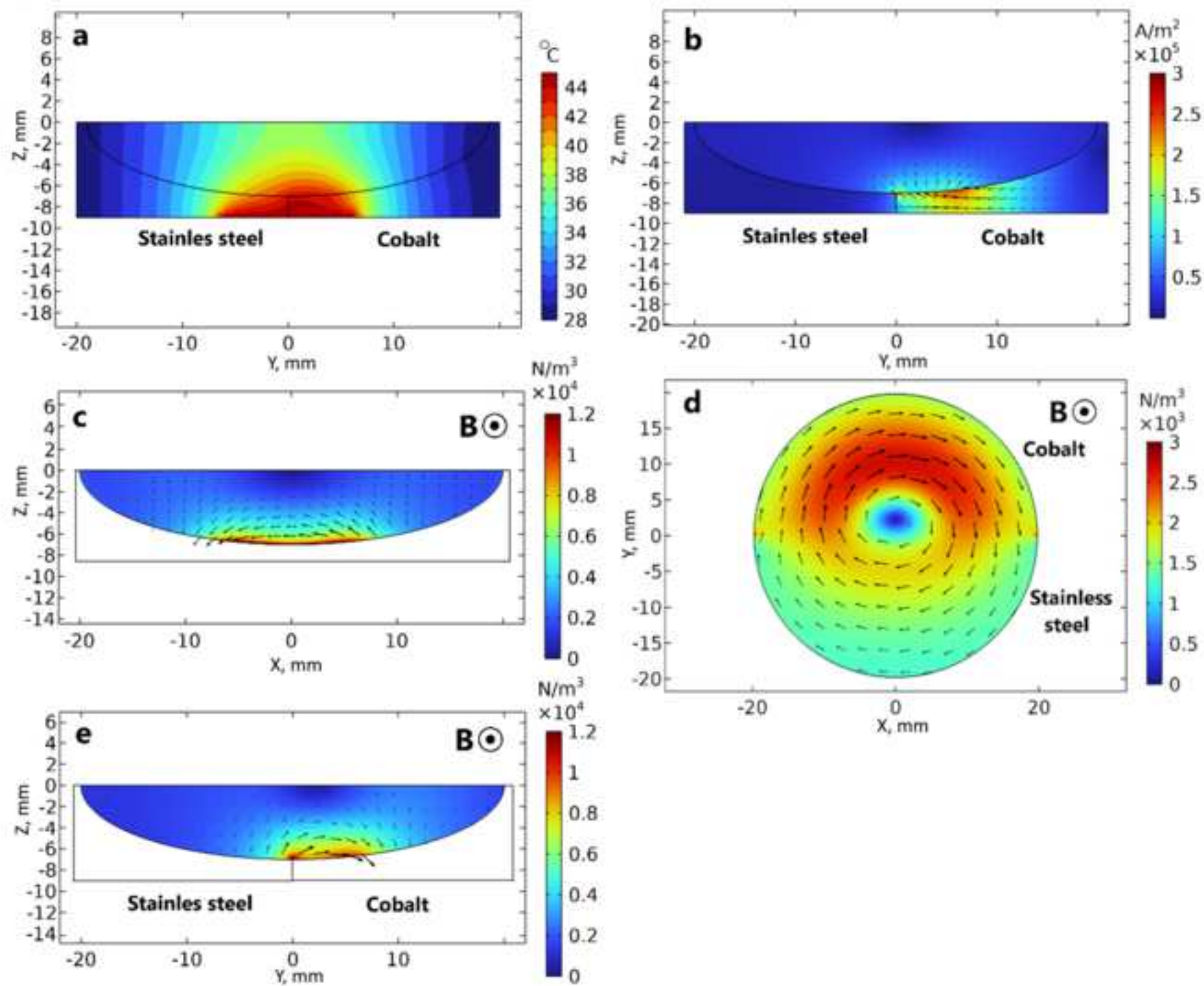


Figure 5

[Click here to access/download;Figure;JOMfig5fix3.png](#)

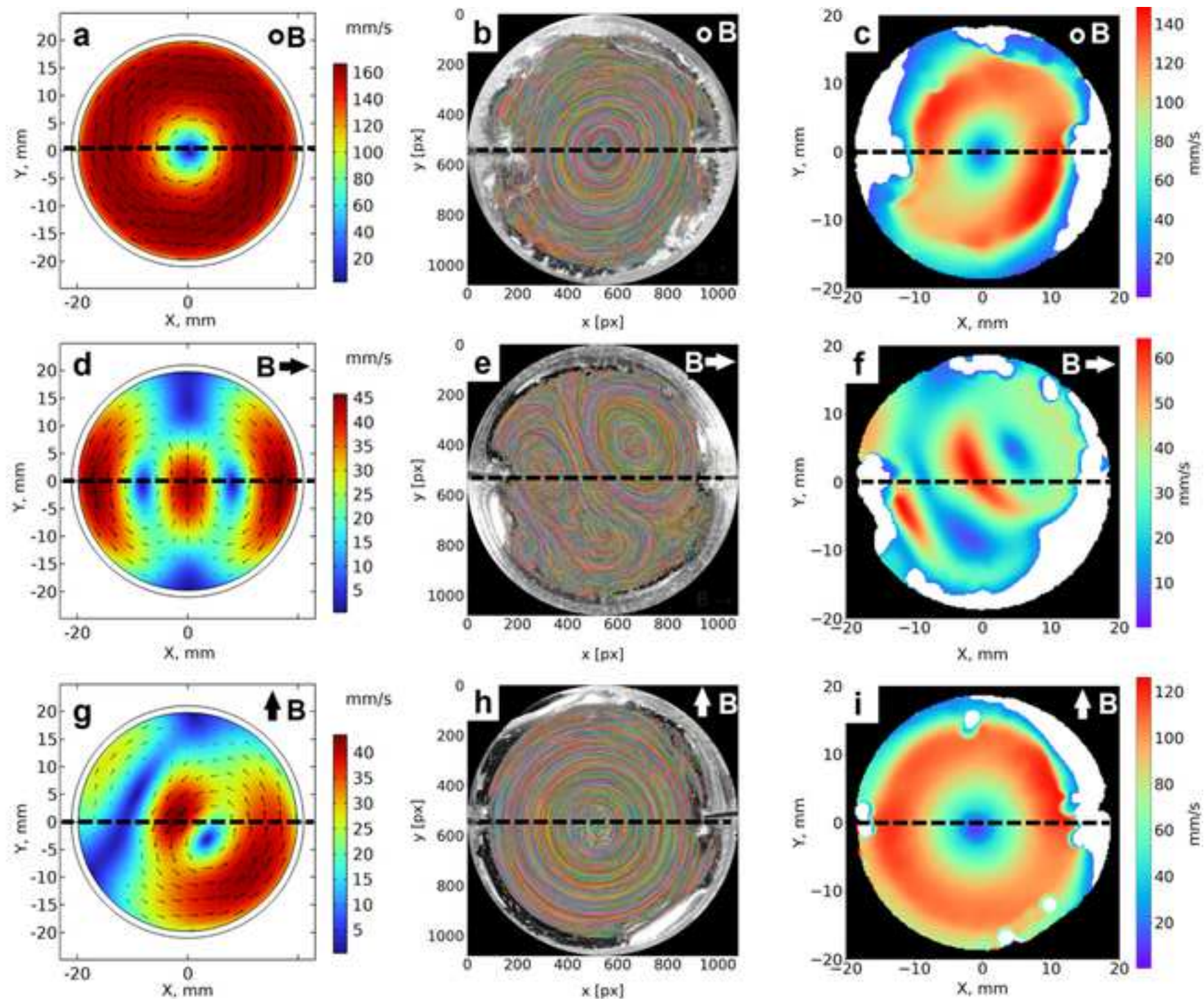


Figure 6

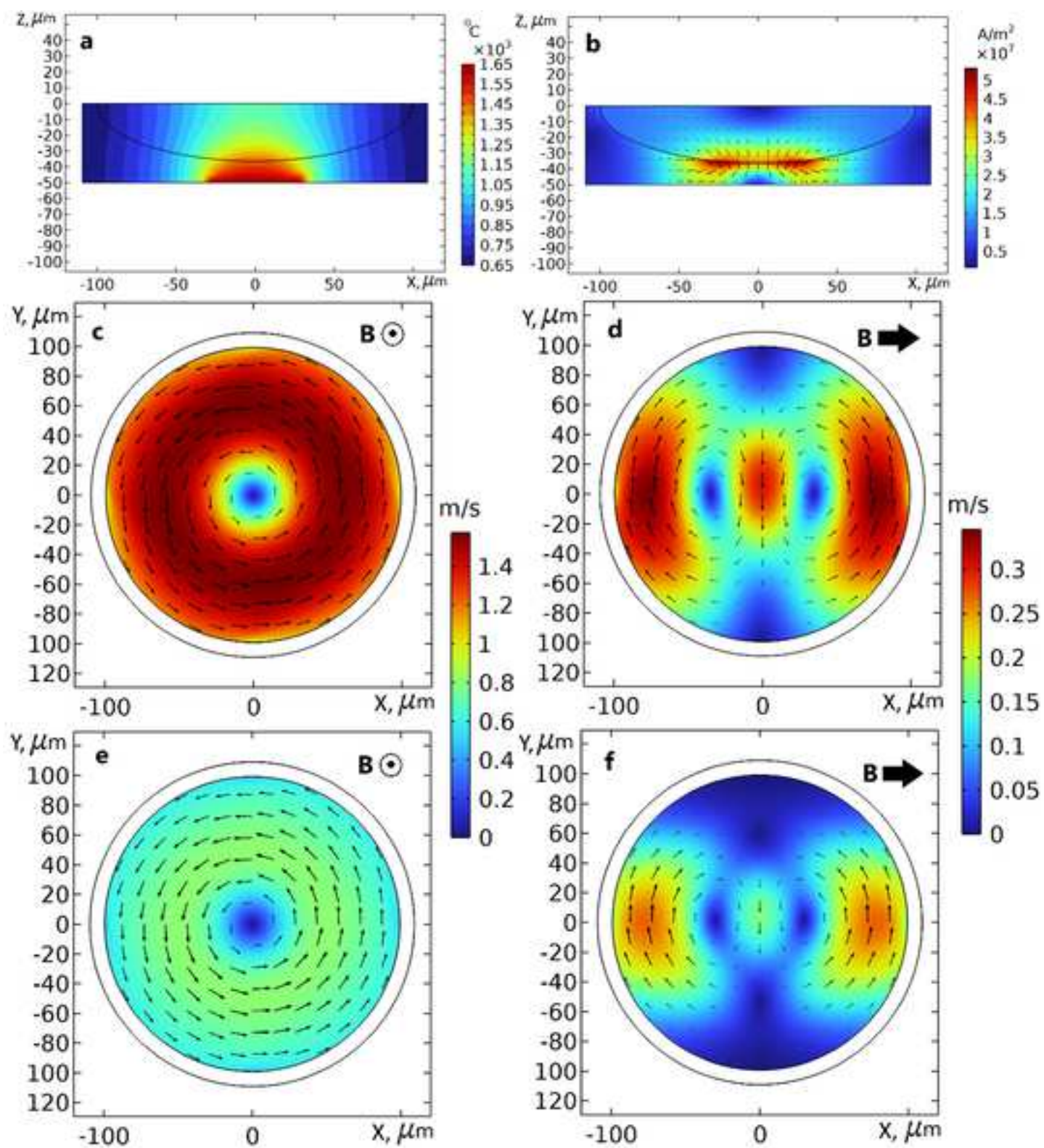


Figure 7

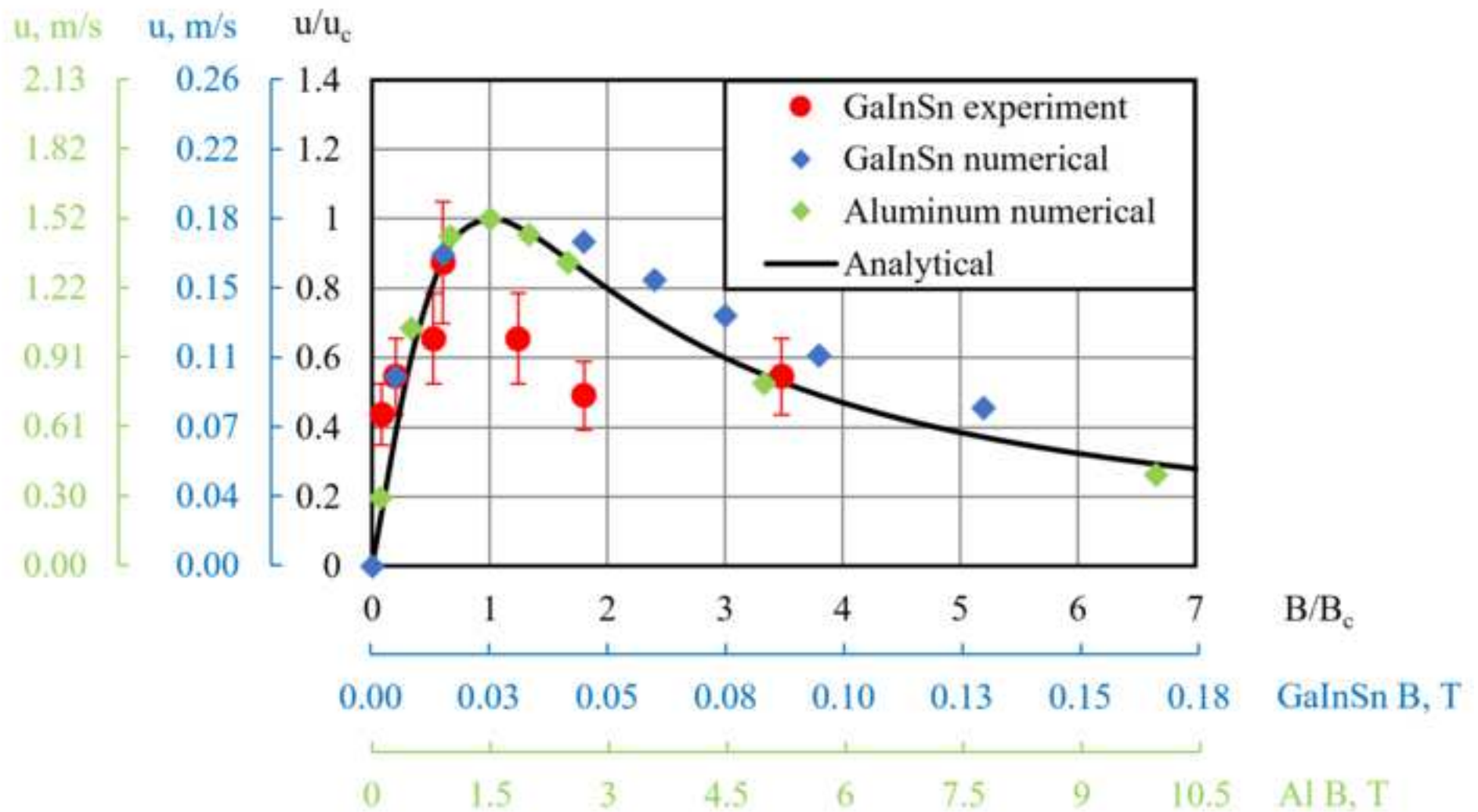


Figure 8

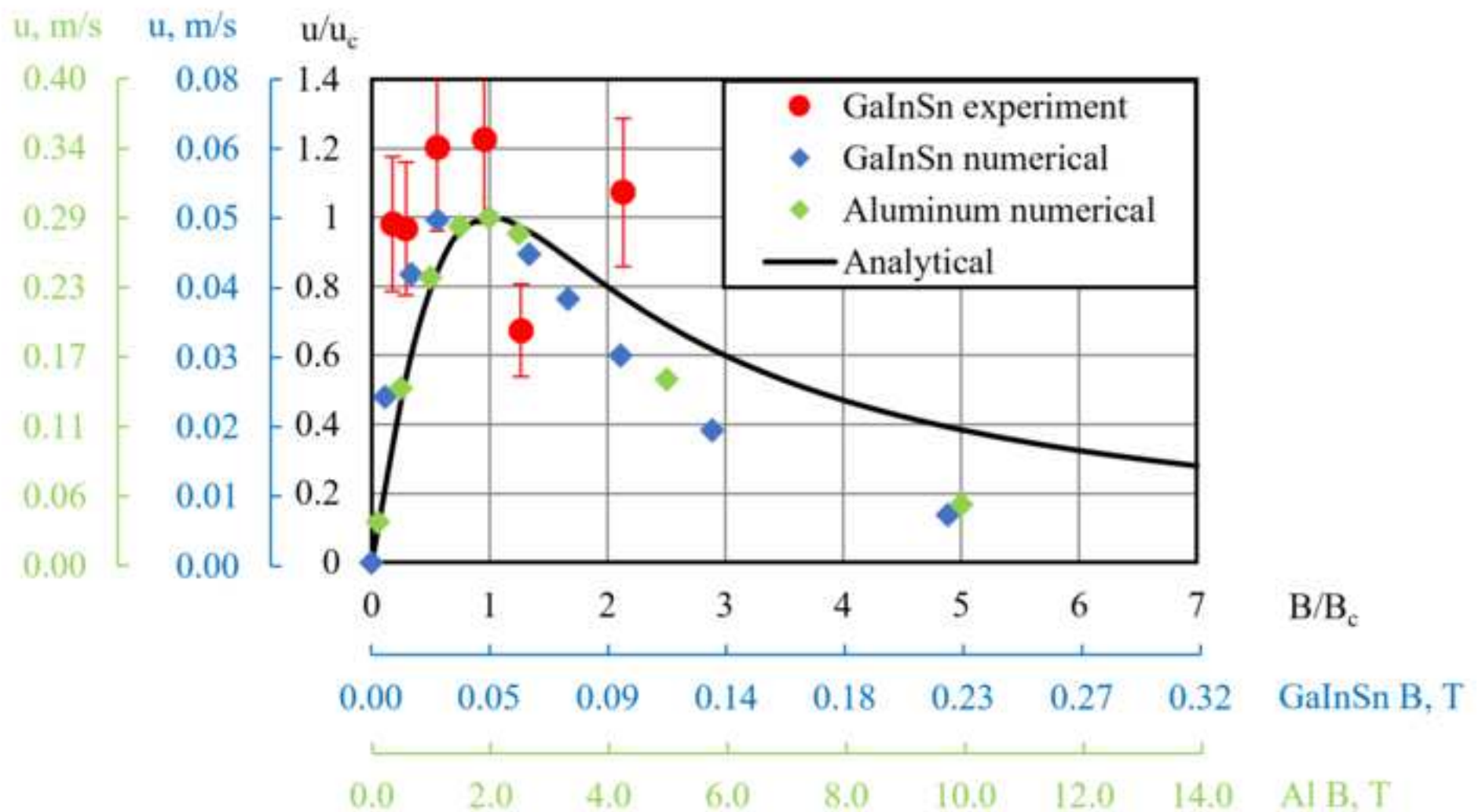


Table 1. Physical properties of the materials used in experiments and numerical models.

Property	Symbol	Cobalt	GaInSn [30]	Stainless steel	Al (at m. p.)	Liquid Al (at m. p.)
Electric conductivity (MS/m)	σ	16	3.3	1.3	6	4
Density (kg/m ³)	ρ	8900	6360	7950	2700	2400
Thermal conductivity (W/m·K)	λ	100	16	14	185	89
Heat capacity (J/kg·K)	c	468	371	482	903	1127
Seebeck coefficient (μV/K)	S	-24	-0.4	0	0	-1
Dynamic viscosity (mPa·s)	μ	-	3	-	-	1
Surface tension (N/m)	γ	-	0.6	-	-	0.8

Model experiment for investigation of thermoelectric magnetohydrodynamics in metal additive manufacturing

Imants Kaldre^{1*}, Valdemars Felcis^{1,2}, Ivars Krastins^{1,2}, Peter Soar²,
Catherine Tonry², Andrew Kao²

¹ University of Latvia, Jelgavas Street 3, Riga, LV-1004, Latvia.

² University of Greenwich, Old Royal Naval College, Park Row, London SE10 9LS, UK.

*Corresponding author: imants.kaldre@lu.lv

Abstract: Metal additive manufacturing is a rapidly growing technology revolutionizing many industries, yet wide adoption is limited due to the unreliability and complexity of the process. Scanning strategies, such as hatching, add further complexity to heat transfer and ultimately microstructure growth. Applying external magnetic fields is a promising technique to improve control of melt flow and heat transfer. High local thermal gradients can cause thermoelectric currents to circulate at the solid-liquid interface. When a magnetic field is applied, a Lorentz force drives fluid flow, which can have significant impact on the melt behavior and solidification outcome. In this work we analyze the impact a static magnetic field has on liquid metal flow using a scale model representative of additive manufacturing which allows us to directly observe and measure the thermoelectric magnetohydrodynamic flow. Experiments with bi-metallic bowl, made of two halves with distinctly different thermo-physical properties, provides an analogy to hatching revealing a strong influence on both thermoelectric currents and ultimately the flow. Through an analytic scaling analysis, the results are compared against numerical models spanning orders of magnitude in both length and velocity, providing a correlation between the model experiment and realistic conditions encountered in industry additive manufacturing processes.

INTRODUCTION

Metal additive manufacturing (AM), often referred to as metal 3D printing, unlocks new possibilities to produce complex custom-shaped parts quickly and without large initial investments. Currently 3D printing is a technique with increasing usage in industry with a wide range of applications and sectors. With rapid global market growth, more resources are being invested in the development of new materials and techniques. AM **has the potential to be** a clean and efficient technology due to minimal waste material and lower energy consumption compared with subtractive manufacturing techniques. During the **AM** process, a small quantity of metal is melted by a laser or an electric arc, which then rapidly solidifies. It enables the production of parts with increased complexity at near net shape compared to conventional machining and casting. AM is primarily used to produce a small number of individual parts rather than large volume production. AM for various metals is already commercially available (e.g. steel, aluminum, bronze, titanium, copper, and tungsten). Despite the tremendous benefits of AM, it is currently less developed as a technology compared to machining and casting, and when designing a new part usually engineers must consider the method which will be used to manufacture it. Wide use of AM is still limited because of expensive and complicated equipment and raw materials [1]. Even for common

materials such as 316L Stainless Steel and aluminum, high quality powder or wire suitable for 3D printing costs up to ten times the price of cast alloy. This raw material cost also only constitutes about one third of additive manufacturing expenses, while the rest is mostly depreciation of machinery and energy consumption [2]. Significant expenses arise due to the slow printing process, because every step requires melting, solidification and cooling down of a small metal quantity, thus when aiming for higher accuracy, printing time increases [3]. The most popular techniques of metal AM are directed energy deposition (DED) and powder bed fusion (PBF). In the DED process metal is fed as powder or wire and then melted by laser or electric arc, and deposited onto a surface where it solidifies, fusing materials together with the printed part. In the PBF process a thin layer of metal powder is spread over the previous layer and then fused by arc or laser at certain spots. Such processes require high accuracy in both raw material dosing and heating power regulation to avoid local overheating and get the correct size and shape of printed metal element. The printhead or laser is moved by CNC (computer numerical control) stepper motors, typically one for each of the three axes, but in some cases more complicated systems are used allowing various rotations and other degrees of freedom [4].

It is important that every time the small droplet-sized liquid metal melt pool solidifies in the same conditions. The melt pool is molten for a very short time (several milliseconds), and the typical cooling rate in metal AM is between 10^3 and even 10^6 K/s. Heat and mass transfer in the molten state and during solidification have a significant impact on the outcome of the solidification process and subsequently solidified material microstructure and properties. One issue is that heat and mass transfer in this ultra-fast micro scale process is difficult to control because it is mainly defined by material properties and conditions which cannot be readily altered [5]. During AM of complex structures, it is difficult to ensure reliability and repeatability during the whole AM process, as thermal conditions while printing the corners or edges of the printed part can be very different. In this case, on one side of the melt pool there is solid metal, while on the other side there is powder or air, thus the temperature field during solidification can be highly distorted. This may cause oriented dendrite growth and lead to asymmetric morphology and properties of the solidified volume. Several approaches have been used to address these issues, such as adjusting the printing parameters depending on the location of the printed piece and regulating the nozzle parameters, like temperature and material feeding rate. This is done using sensors, video processing, and machine learning methods to predict the optimum set of parameters for each printing step depending on its location. This has solved some of the problems, but still additional melt pool control methods are needed to further unlock AM capabilities and enable the manufacturing of new materials [6,7]. Accuracy and reliability of AM could be improved if behavior of the liquid metal volume and solidification parameters could be better controlled [8, 9, 10].

Aluminum based alloys are one of the most used metals in automotive and aerospace applications, primarily because of their exceptional combination of low density, high specific strength and excellent resistance to corrosion. There are many different aluminum alloys suitable for various additive manufacturing approaches, but because of the high cooling rate only a handful of them are suited for AM. Wire additive manufacturing (WAM) is the fastest additive manufacturing process, allowing it to quickly and reliably produce complex parts which do not require high accuracy or can later be machined to finish. WAM is in principle a welding process where the part is

manufactured by welding layer on layer using electric arc or laser printhead. Specifically high strength aluminum alloys such as 2, 6 and 7 series are difficult to produce by AM due to high internal stresses after solidification, leading to porosity and cracking. There are some exceptions e.g. Scalmalloy which utilizes Scandium (Sc), a rare, high-cost metal additive to avoid cracking via the mechanism of acting as a nucleation center for the solidification. This alloy can resist ultra-high (10^6 K/s) cooling rates, but complex production of powder and low availability of Sc limits the scalability of the application of this material [11].

A promising approach for better melt pool control is using contactless electromagnetic methods, where applied magnetic fields induce forces in the molten metal. There are numerous scientific studies about metallic alloy solidification under various magnetic fields, showing that heat and mass transfer can be modified resulting in a significant effect on the solidified metal [12, 13, 14] including beneficial effects like grain refinement [15, 16]. Magnetohydrodynamics (MHD) studies the various phenomena associated with the interaction between magnetic fields and electrically conducting liquid media. MHD methods for improved control of the liquid metal are recently considered as a promising approach in metal AM with grain refinement also observed [17, 18]. Magnetic fields in AM have also been shown to address various problems such as precisely timed, exact size droplet ejection from the printhead [19] and affect the heat transfer in the melt pool [20].

During AM extremely high local thermal gradients are present in the melt pool and nearby solid zone. Seebeck coefficient or absolute thermoelectric power can be different for liquid and solid metals. It is an electron transport property, and it can be discontinuous during phase change. If there is a thermal gradient along the interface, then a voltage difference is also generated along the solid-liquid interface. Thermoelectric currents then circulate at the solid-liquid interface as a result of this voltage difference. The current originates from the Seebeck effect between solid and molten material, and its amplitude is proportional to temperature gradient, electrical conductivity of both materials and differential Seebeck coefficient between solid and liquid states of the metal. The current density $\mathbf{J}$ is given by Ohm's law

$$\mathbf{J} = \sigma(\mathbf{E} - S\nabla T + \mathbf{u} \times \mathbf{B}) \quad (1)$$

where σ is the electrical conductivity, $\mathbf{E}$ is the electric field, S is the Seebeck coefficient, T is the temperature, $\mathbf{u}$ the fluid velocity and $\mathbf{B}$ the magnetic field. The Seebeck coefficient is an electron property (analogous to P and N type semiconductors) and therefore for many materials it is different for solid and molten states at the melting temperature. The thermoelectric currents can circulate at very small scales, comparable to the melt pool size itself and the current density can reach extremely high magnitude in a small volume, because of the high electric conductivity and temperature gradient. If a magnetic field is applied it creates a Lorentz force, $\mathbf{J} \times \mathbf{B}$, which can drive liquid metal flow from the $\sigma S\nabla T$ term, but also damp the flow from the induced currents ($\sigma \mathbf{u} \times \mathbf{B}$ term). This driving phenomenon is called thermoelectric magnetohydrodynamics (TEMHD), also commonly referred to as thermos-electro-magnetic convection, TEMC [21, 22, 23].

This work aims to quantify the TEMHD role in metal AM by designing and conducting a low-temperature lab-scale model experiment which allows for direct optical observation of the TEMHD generated liquid metal flow. The flow varies with different

applied static magnetic field orientations and strength. Our recent work on similar scale models to quantify this effect demonstrates the possibility to achieve considerable liquid metal velocity by means of TEMHD and electric current injection [24, 25]. Numerical models of this TEMHD case also showed a good agreement to the experiment, thus model experiments can be valuable for prediction of behavior of liquid metal in realistic aluminum alloy processes. TEMHD acts as a volume force, which in real AM processes is present in the small melt pool, typically a few hundred micrometers in diameter. However, even with a moderate magnetic field, on the order of 1 T and within the range of permanent magnets, the thermoelectric force can become dominant, competing with or overcoming other inherent forces such as Marangoni stress and buoyancy. For example, recent experiments at synchrotron radiation facilities indicate that TEMHD can be comparable to strong Marangoni flows (1 m/s) present in the melt pool of laser AM with magnetic field strengths in the range of permanent magnets (0.5 T) [26, 27].

METHODOLOGY

The experimental setup consists of a shallow metallic bowl with an inner diameter of 40 mm and depth of 10 mm at the center. The magnetic field is applied by a permanent magnet assembly, which allows for the field orientation to be changed and a magnitude from 0 to 100 mT [28]. This magnet assembly can create a magnetic field either in transverse or axial directions. The field strength can be adjusted by moving the magnets closer in or further apart. In this work, we consider two bowls, the first is entirely made of Cobalt (Fig. 1a) and the second, a bi-metal bowl, consists of two halves, one half is Cobalt, and the other is Stainless Steel (Fig. 1b). The second case breaks the axial symmetry as Cobalt has a high $S = -24 \mu\text{V/K}$, while S for Stainless Steel is close to $0 \mu\text{V/K}$. Heating is introduced from the bottom of the bowl using an electrically heated copper rod in contact with the bowl. Heat is extracted from the outer edge of the bowl by a water-cooled copper pipe soldered to the side of the bowl. Heating from the bottom allows the free surface to be unobscured for observations. The overall scheme of the experiment is shown in Fig. 1c. The temperature is measured by several thermocouples, which are placed outside the bowl or in the melt pool in various places. This temperature data is then used to provide boundary conditions for the numerical simulations.

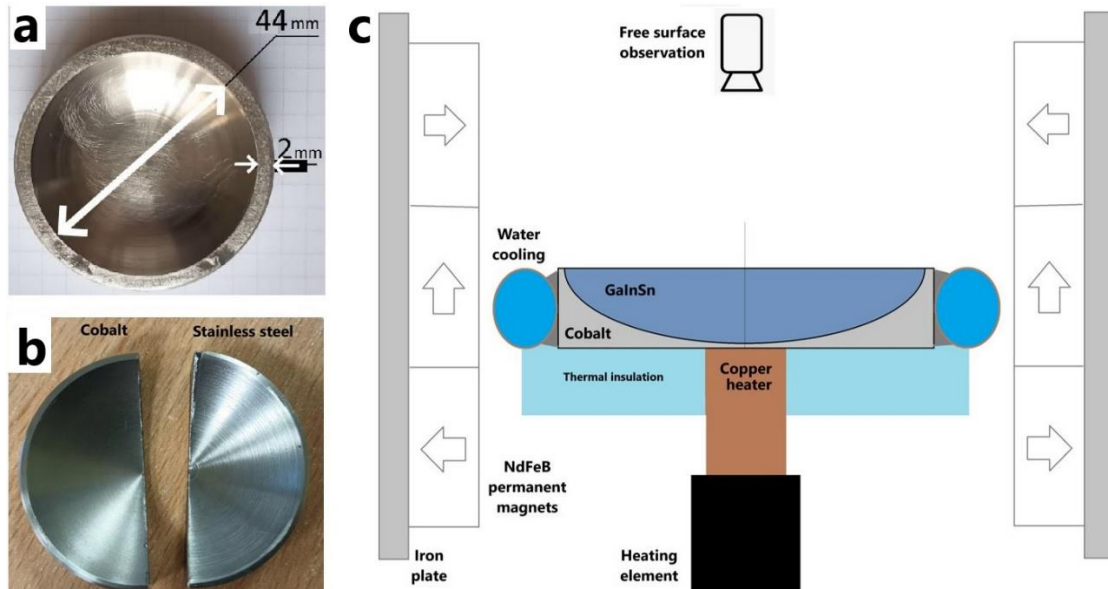


Figure 1. Experimental setup: a) Cobalt bowl; b) Bi-metal Cobalt-Stainless Steel bowl; c) Schematic cross section of the experimental setup (not to scale).

The liquid GaInSn free surface is covered with a thin layer of HCl aqueous solution (3-5 %) to break the oxide film and create a protective layer. The metal surface flow pattern is observed by a digital camera, recording 60 frames per second videos. Oxide particles and small bubbles from the reaction with the acid conveniently serve as tracer particles for the liquid metal surface flow visualization and video processing to obtain the surface velocity distribution. The flow is measured from the videos by tracing the particles and bubbles floating on the surface using the Trackpy Python package [29], which allows mapping the surface velocity distribution. Particles are automatically selected by particle size and brightness. Each particle is tracked frame by frame. To create particle trajectories, the built-in predictor function is used that estimates the instantaneous velocities of a group of nearby particles. Obtained trajectories can then be processed to calculate point velocities at measured particle positions by using distance traveled in a single frame and camera framerate. Across a single two minute measurement video around a million particles can be tracked across all frames. Therefore, distance-weighted averaging of velocities was used to create a structured grid of velocities with a resolution of 0.2 mm to eliminate most particle tracking errors and allow for simpler post processing of the data. The averaging procedure is to take a particular point on the chosen grid, then taking points in a 1.41 mm circle around it and taking an average weighted by the distance to the chosen grid point. A high-speed camera is positioned directly above the melt pool, recording the top surface showing the flow through oxides and bubbles on the surface. Fig. 2 shows a typical example of experimental data, where Fig. 2a shows an image of the raw data and Fig. 2b shows the particles detected by tracking algorithm. Using successive frames streamlines shown in Fig. 2c and velocity contours can be reconstructed and compared to the numerical simulations. Due to reflections of the light on the curved surface saturating the optical imaging, in some regions particles could not be tracked and have been blanked (white) in the results sections.

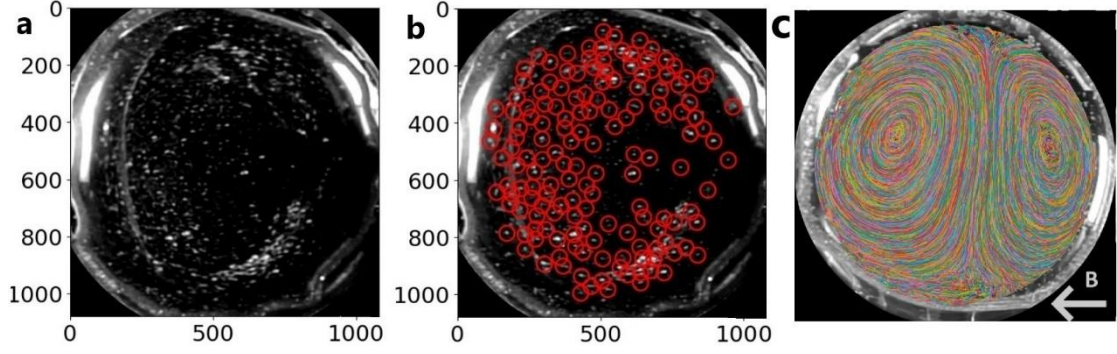


Figure. 2. Video processing and particle tracking: a) Video frame with liquid GaInSn surface, b) Selected particles which are tracked, c) Particle trajectories ($B=75$ mT).

To better understand the physical processes in the melt pool, numerical simulations are conducted using COMSOL Multiphysics 6.0. The temperature distribution is simulated using experimental measurements as boundary conditions. Thermoelectric currents are calculated from the temperature field using Ohm's law (Eq. 1). The Lorentz force, $\mathbf{J} \times \mathbf{B}$, is then calculated by adding a source term in the steady-state Navier-Stokes equation given by

$$\rho \mathbf{u}(\nabla \mathbf{u}) = -\nabla p + \mu \Delta \mathbf{u} + \sigma(\mathbf{E} + \mathbf{u} \times \mathbf{B} - S\nabla T) \times \mathbf{B} \quad (2)$$

where ρ is the density, p the pressure and μ the dynamic viscosity. The force $\sigma \mathbf{u} \times \mathbf{B} \times \mathbf{B}$ is the electromagnetic damping force, common to MHD problems.

Other effects considered are Marangoni surface force which originates from temperature dependence in the surface tension and natural convection due to the density having a temperature dependence. While in real AM processes Marangoni is typically the primary driver, in this model experiment, due to the large length scales, these were found to be at least order of magnitude smaller than Lorentz forces considered and thus neglected in further calculations. Physical properties of the materials used in the experiments, numerical models, and analytical calculations are given in Table 1. For comparison, liquid and solid aluminum properties at the melting temperature are included in the table.

Table 1. Physical properties of the materials used in experiments and numerical models.

Property	Symbol	Cobalt	GaInSn [30]	Stainless Steel	Al (at m. p.)	Liquid Al (at m. p.)
Electric conductivity (MS/m)	σ	16	3.3	1.3	6	4
Density (kg/m ³)	ρ	8900	6360	7950	2700	2400
Thermal conductivity (W/m·K)	λ	100	16	14	185	89
Heat capacity (J/kg·K)	c	468	371	482	903	1127
Seebeck coefficient (μ V/K)	S	-24	-0.4	0	0	-1

Dynamic viscosity (mPa·s)	μ	-	3	-	-	1
Surface tension (N/m)	γ	-	0.6	-	-	0.8

RESULTS AND ANALYSIS

Cobalt Bowl

Heat flux is primarily in the radial direction, extending from the central hot spot at the bottom to the water-cooled edge of the bowl, creating a radially symmetric temperature distribution. If the differential Seebeck coefficient between solid and liquid metals is non-zero, then the thermoelectric current will originate at the interface forming an axially symmetric path, in this case from the center to the side through the liquid metal and return through the solid bowl. The temperature field in the experiment is determined based on thermocouple measurements at certain points inside and outside of the melt pool. The typical temperature difference during experiment between the bottom of the melt pool and outer edge is around 10 °C, thus in the model experiment a typical thermal gradient is 500 K/m. Using these measured values as boundary conditions, the numerically calculated temperature field and thermoelectric current distribution in Cobalt bowl are shown in Fig. 3a and 3b.

While heating from the bottom gives a different temperature field compared to AM processes that are heated from the top, the resultant thermoelectric currents are quite similar. The current emanates normal to the base of the bowl in the axial direction, circulating into a radial current through the liquid and then returning through the Cobalt bowl (Fig. 3b). Such behavior is also predicted in direct models of the AM process [22].

When an axial magnetic field is applied, the field only interacts with the radial component of $\mathbf{J}$ and the Lorentz force becomes angular, driving a rotational flow (Fig. 3(c-e)). An axial field retains the symmetry of the system, however in the case when a transverse magnetic field is applied, this symmetry is broken. The magnetic field primarily interacts with the axial current generating a force normal to the field and along the bowl. The corresponding flow traverses the bowl, but due to the geometry leads to a stagnation point at the edge. As the force is concentrated in the center, to preserve continuity, the flow reverses direction forming a pair of vortices (Fig. 3 (f-h)). For the two magnetic field orientations an excellent agreement is found both in terms of the magnitude of the flow and the direction of flow. The results are also consistent in terms of the number of vortices and directions with simulations of the AM process [22]. In the transverse case one of the vortices is slightly larger than the other, which can be attributed to the difficulty of applying a perfectly centered heat source. Slight deviations from the middle skew the vortices, while in the axial case this effect is much smaller. The results show that even with only a 10 K temperature difference between the bottom and the side of the melt pool can drive TE current of 10^5 A/m² and with modest magnetic field of 15 mT TEMHD velocities can reach up to 120 mm/s with axial magnetic field and 50 mm/s with transverse field.

current in the Steel is much smaller (practically zero) compared to Cobalt. There is no current between the Cobalt and the Steel and consequently the current passes along the seam (in the z direction) across the Cobalt – GaIn interface. The current then circulates through the liquid GaIn and back into the Cobalt. With no current in the Steel, there is no circulation between the GaIn and Steel and the current is focussed in the liquid region above the Cobalt half of the bowl. Consequently, when a magnetic field is applied the Lorentz forces are also concentrated in this region. Figs. 4(c-e) show the Lorentz force for each orientation of the magnetic field. Fig. 4d for the axial field and Fig 4e for the field aligned along the seam particularly highlight how the Lorentz force is focused in the Cobalt region.

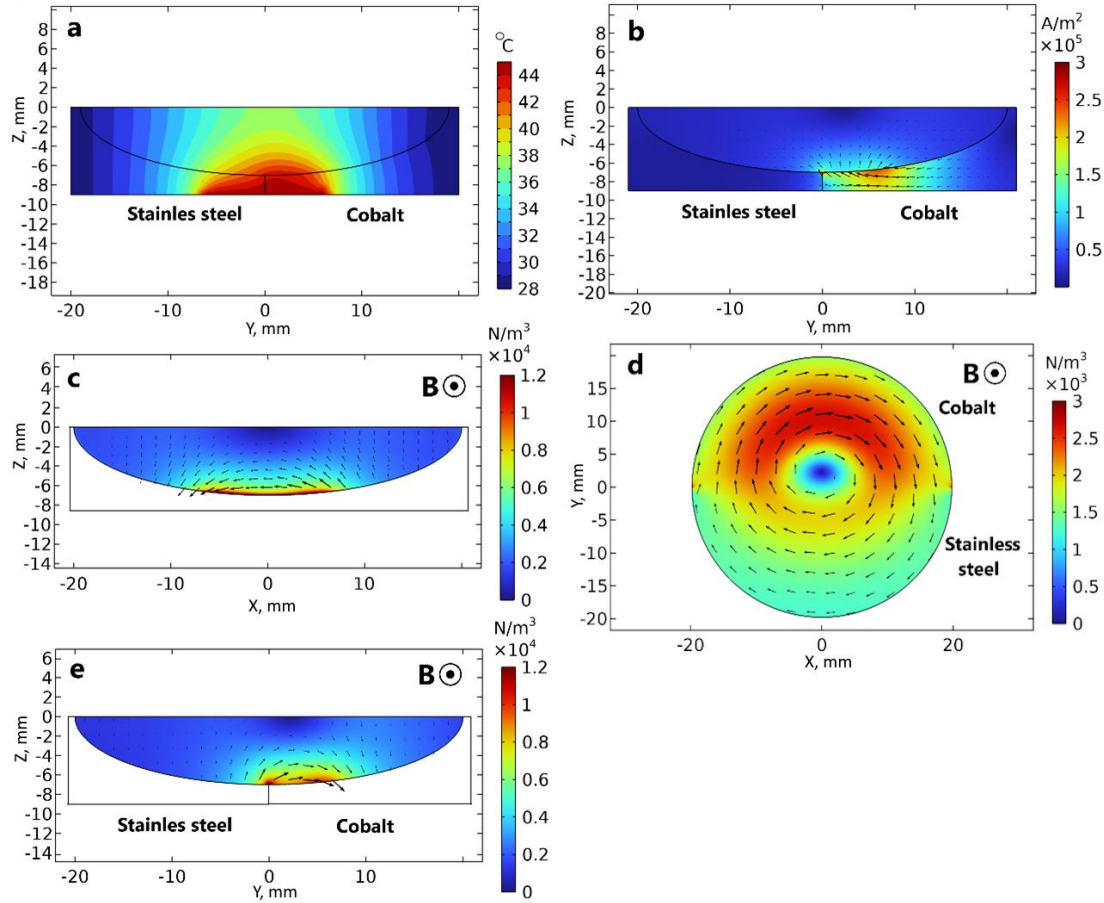


Figure 4. Numerical simulation of bi-metal bowl: a) Thermal field, b) Current distribution. Lorentz force distribution with $B=15$ mT: c) Magnetic field across the seam, d) Axial magnetic field, e) Magnetic field along the seam.

Due to the skewing of the thermoelectric currents, the symmetry of the system is further broken compared to the pure Cobalt bowl. There are therefore three magnetic field orientations to consider (in order of breaking symmetry): an axial field, a transverse field across the joint and a transverse field along the joint. Fig 5. shows all these cases and comparison between numerical simulations and experimental observations.

With an axial field, the Lorentz force is still predominantly angular, but with the highest magnitudes in the Cobalt region. The flow then accelerates in this region and to preserve continuity a rotational flow still forms across the entire bowl, but the highest velocities are now in the Cobalt region (Fig. 5 (a-c)). Applying a transverse magnetic field

along the joint line of the bi-metal bowl preserves the symmetry plane across the joint line. Although the Lorentz force is focused in the Cobalt region, it drives flow along this symmetry plane, and like the pure Cobalt bowl case, a stagnation point form on the edge and combined with continuity again leads to the formation of two symmetric vortices (Fig. 5(d-f)). The symmetry of the system can be further broken by applying a transverse magnetic field across the bi-metal joint. The numerical modelling suggests that this should lead to a more complex system of vortices with the largest vortex in the Cobalt region, followed by a smaller one in the Stainless Steel region (Fig. 5(g)). However, the experimental results are similar to that of the axial case (Fig. 5(h-i)), but a key difference is that the orientation of the flow is reversed and the mechanism for the rotational flow is somewhat different. In the axial case $\mathbf{J} \times \mathbf{B} \approx J_r B_z \hat{\theta}$, where J_r is the radial current and is positive and B_z is the axial field and is also positive creating a positive angular ($\hat{\theta}$) force (clockwise). However, for this transverse case $\mathbf{J} \times \mathbf{B} \approx -J_z B_y \hat{x}$, where J_z and B_y are positive, but the resultant force is negative in $\hat{x}$. Due to the skewed currents this force is off center compared to the perpendicular transverse magnetic field case and consequently drives the apparent angular flow in a counter-clockwise fashion. The numerical results also represent an idealized scenario, but as seen in the transverse pure Cobalt bowl case, the system is sensitive to small asymmetries. The numerical results show that there is a dominant vortex and it is highly likely that this has expanded further to occupy the entire surface.

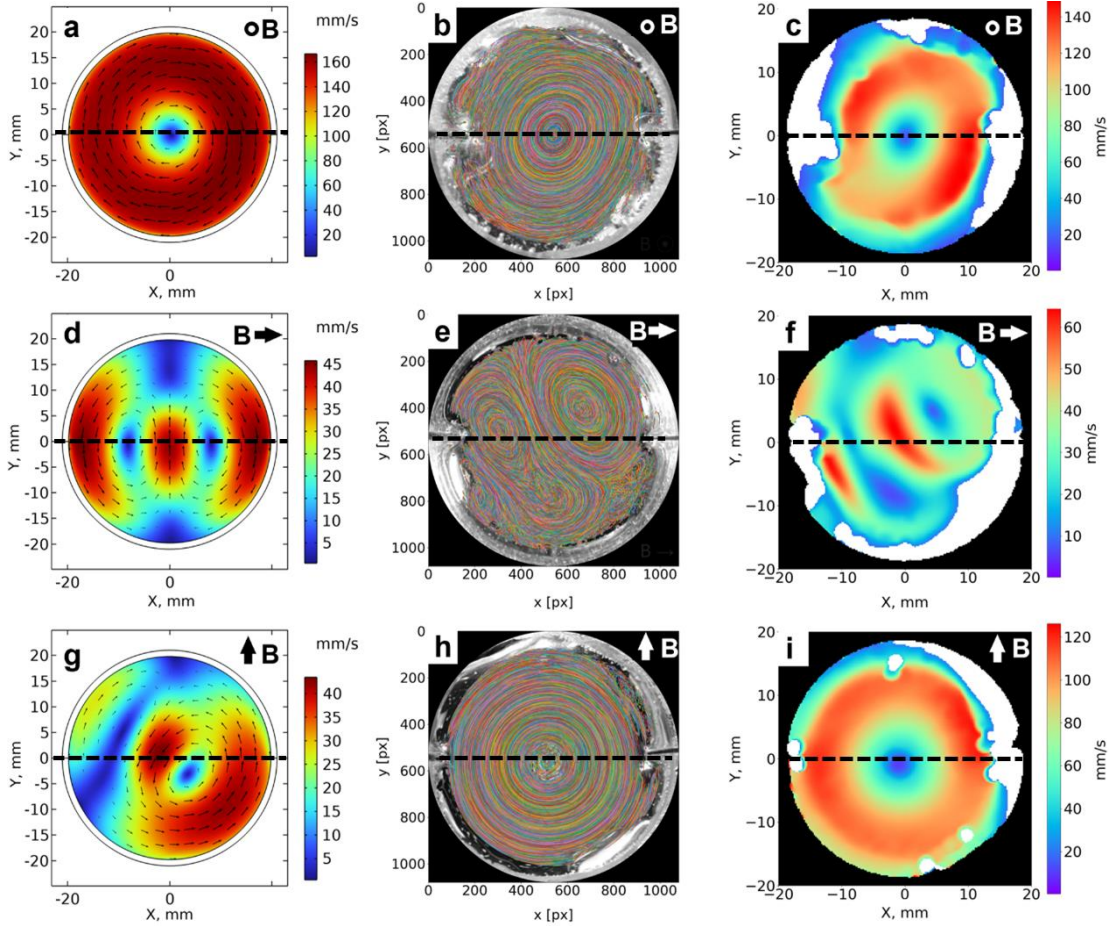


Figure 5. TEMHD velocity in bi-metal bowl. (a-c) Axial magnetic field $B=20$ mT: a) Numerical simulation, b) Particle traces, c) Velocity contour. (d-f) Transverse magnetic field along the seam $B=25$ mT. d) Numerical simulation, e) Particle traces,

f) Velocity contour. Transverse magnetic field across the seam $B=20$ mT: g) Numerical simulation, h) Particle traces, i) Velocity contour. **Seam is highlighted by horizontal dotted line with cobalt being the top part in all figures.**

Application to AM Process

TEMHD in actual AM arises from large volume force, which is present in small melt pool typically of few hundred micrometers. Even with moderate magnetic fields, thermoelectric force can become a dominant force acting on the liquid metal. To assess the forces in real AM case the same model is calculated for Aluminum melt pool 0.2 mm across using the properties from Table 1. Numerical simulation results are shown in Figure 6. Figs. 6a and b show the temperature field and the thermoelectric current distribution in a realistic Aluminum AM case. In this case the temperature gradient is on the order of magnitude of 10^7 K/m and thermoelectric currents are as high as 5×10^7 A/mm². The corresponding velocity distribution at the liquid metal surface at 1.5 T are given in Figs 6c and 6d for the axial and transverse magnetic fields respectively, and show similar characteristics to the pure Cobalt case given in Fig 3, except the length scales are much smaller and velocities much higher. Applying a very high magnetic field of 5 T is shown in Figs 6e and 6f for the axial and transverse cases respectively, where through the action of the electromagnetic damping force the flow field is modified. In both cases the velocity magnitude is reduced, while in the transverse case the flow morphology is also somewhat modified with the central maximum being damped more severely compared to the edges of the melt pool.

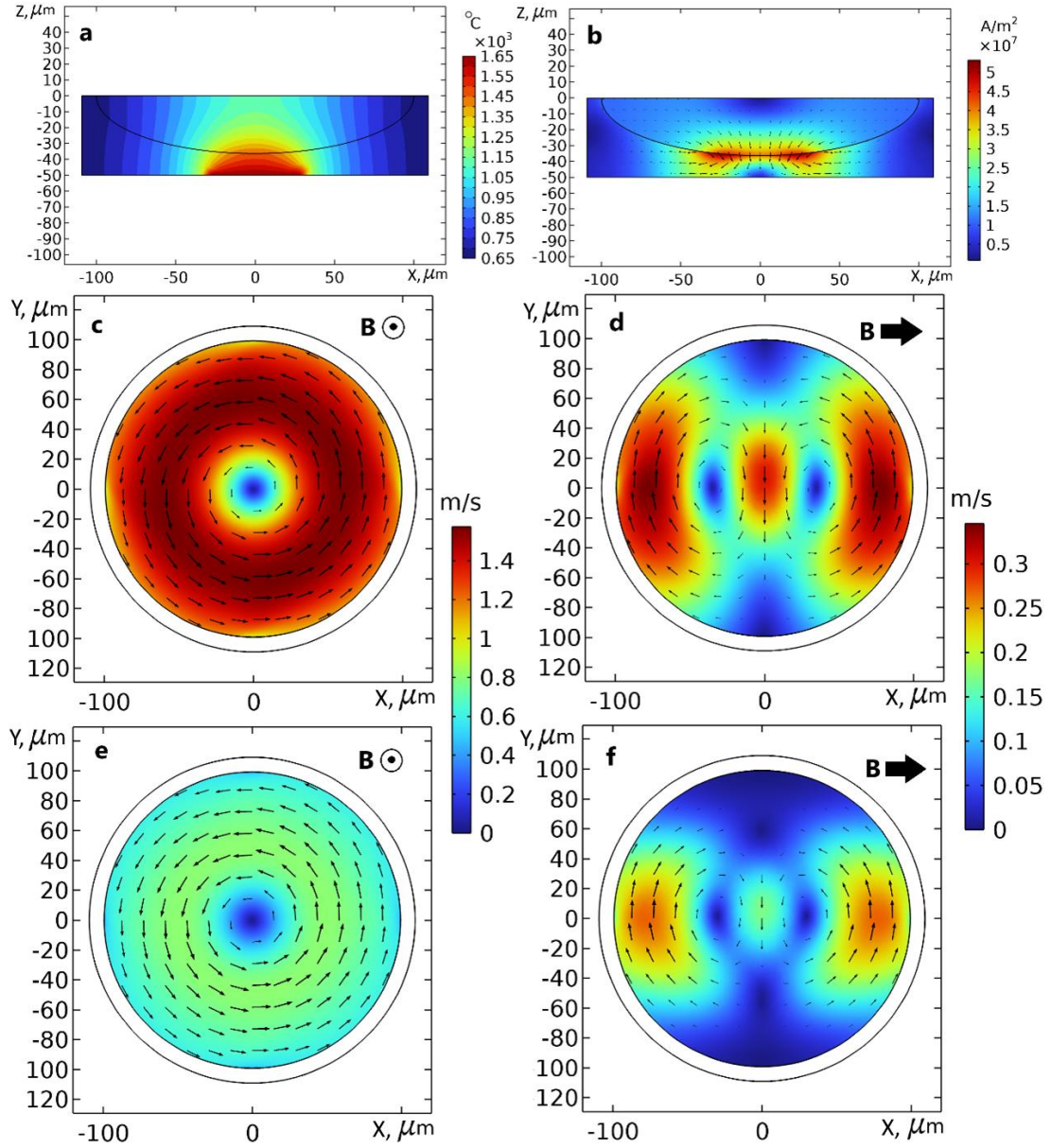


Figure 6. Numerical simulation of TEMHD velocity in Aluminum melt pool: a) Temperature field, b) Thermoelectric current distribution. TEMHD surface velocities: c) Axial magnetic field of 1.5 T, d) Transverse magnetic field of 1.5 T, e) Axial magnetic field of 5 T, f) Transverse magnetic field of 5 T.

To directly compare the bowl experiments to more industry relevant processes such as AM, where length scales and magnetic field intensities are contrastingly different, the following derives an analytical approach informed by numerical simulations. Taking the steady-state Navier-Stokes equation (Eq. 2) and neglecting the inertial term leads to

$$-\nabla p + \mu \nabla^2 \mathbf{u} + \sigma \mathbf{E} \times \mathbf{B} + \sigma \mathbf{u} \times \mathbf{B} \times \mathbf{B} - \sigma S \nabla T \times \mathbf{B} = \mathbf{0}. \quad (3)$$

The electric field $\mathbf{E}$ acts to preserve continuity of charge ($\nabla \cdot \mathbf{J} = 0$) and in this context, we assume that it acts against the thermoelectric field such that $\mathbf{E} = C_E S \nabla T$, where $0 < C_E \leq 1$. The case when $C_E = 1$ represents a situation where the electric field perfectly balances the thermoelectric field and no thermoelectric current forms, such a

case can exist when the medium is homogenous. Conversely, $C_E \neq 0$ if $|S|$, $|\nabla T|$ and σ are all greater than zero, as the thermoelectric field, $S\nabla T$, (or more specifically the thermal gradient) cannot form closed paths. Through a similar argument, ∇p serves to preserve continuity of mass ($\nabla \cdot \mathbf{u} = 0$) and again, in this context, will act against the driving thermoelectric Lorentz force, yielding the assumption $-\nabla p = C_p \sigma S \nabla T \times \mathbf{B}$. Then by approximating $S \nabla T \times \mathbf{B} = S |\nabla T| |\mathbf{B}|$, the proportionality constants can be combined with the thermoelectric term into $C_0 = 1 - C_E - C_p$, where $0 \leq C_0 \leq 1$. The other terms can be approximated as $\mu \nabla^2 \mathbf{u} = \mu \frac{|\mathbf{u}|}{L^2}$, and $\sigma \mathbf{u} \times \mathbf{B} \times \mathbf{B} = \sigma |\mathbf{u}| |\mathbf{B}|^2$, where L is the characteristic length. This leads to the solution for the velocity as a function of the magnetic field,

$$|\mathbf{u}| = \frac{C_0 \sigma S |\nabla T| |\mathbf{B}|}{(\sigma |\mathbf{B}|^2 + \frac{\mu}{L^2})} \quad (4)$$

The critical magnetic field, $|\mathbf{B}_c|$, can be determined from Eq. 4 when $\frac{\partial |\mathbf{u}|}{\partial |\mathbf{B}|} = 0$. The final expression for that is $\sigma |\mathbf{B}|^2 = \frac{\mu}{L^2}$ which is the solution when the Hartmann number is 1,

$$|\mathbf{B}_c| L \left(\frac{\sigma}{\mu} \right)^{\frac{1}{2}} = \text{Ha} = 1. \quad (5)$$

For a given viscosity and electrical conductivity, this condition is satisfied by the product of the critical magnetic field and characteristic length scale. In both the bowl experiment and AM processes defining the characteristic length scale is not straightforward, it represents the viscous boundary layer, but in turn this could be related to the dimensions of the melt pool (e.g. width or depth) or an associated length scale of the current. In this solution we instead define the critical magnetic field from the numerical solutions, which in turn yields values for the length scale. For the bowl, $|\mathbf{B}_c| = 0.03$ T and $L = 1.05$ mm, and for the Aluminum AM process, $|\mathbf{B}_c| = 1.5$ T and $L = 21$ μm , where these length scales are at least 6 times smaller than the depth, but appear to correspond to the length scales of the thermoelectric currents into the melt. In general, this is also related to the morphology of the melt pool but can be considered constant for a given morphology. Substituting $L = \frac{1}{|\mathbf{B}_c|} \left(\frac{\mu}{\sigma} \right)^{\frac{1}{2}}$ back into the velocity solution gives

$$|\mathbf{u}| = \frac{C_0 S |\nabla T| |\mathbf{B}|}{(|\mathbf{B}|^2 + |\mathbf{B}_c|^2)} \quad (6)$$

and at the critical magnetic field, $|\mathbf{B}| = |\mathbf{B}_c|$, gives the critical velocity, $|\mathbf{u}_c|$, where

$$|\mathbf{u}_c| = \frac{C_0 S |\nabla T|}{2 |\mathbf{B}_c|} \quad (7)$$

Taking the ratio of the velocity, Eq. 6, to the critical velocity, Eq. 7, gives

$$\frac{|\mathbf{u}|}{|\mathbf{u}_c|} = \frac{2 |\mathbf{B}_c|^2}{(|\mathbf{B}|^2 + |\mathbf{B}_c|^2)} \frac{|\mathbf{B}|}{|\mathbf{B}_c|}. \quad (8)$$

This form gives a direct way to compare the disparate cases of the bowl experiment and the AM process. When $|\mathbf{B}| = |\mathbf{B}_c|$, the right-hand side becomes unity as this represents

the solution of $|\mathbf{u}| = |\mathbf{u}_c|$. Interesting examples of this solution are when the magnetic field is either half the critical field, $|\mathbf{B}| = |\mathbf{B}_c|/2$ or double $|\mathbf{B}| = 2|\mathbf{B}_c|$, both giving $|\mathbf{u}|/|\mathbf{u}_c| = 4/5 = 0.8$. With reference to the Aluminum AM case from Figure 6 and related experiments, although the critical field may be in the region of 1.5 T, applying a magnetic field of 0.5 T e.g. ref [31], a third of the critical field can still drive a significant flow of 60% compared to the critical field. However, as shown in Figure 6, even with a magnetic field potentially an order of magnitude larger (5 T), TEMHD would still be over 50% of its critical value and therefore for most practical applications it would be near impossible to damp out TEMHD even with superconducting magnets.

In essence this solution scales both the velocity axis by $|\mathbf{u}_c|$ and magnetic field axis by $|\mathbf{B}_c|$, where the critical point is at (1,1). This same scaling can be applied to both the bowl (numerical model and experimental data) and AM process modelling, allowing for a direct comparison, where each case is scaled against its own critical field and critical velocity. In the purely analytic case C_0 vanishes when scaling against the critical velocity, but to scale the numerical simulations and experimental data, C_0 is captured from the predicted critical velocity and critical magnetic field i.e. $C_0 = 2|\mathbf{u}_c||\mathbf{B}_c|/S|\nabla T|$.

Figures 7 and 8 show a comparison for the bowl, the AM process and the analytic solution for an axial magnetic field (Figure 7) and a transverse magnetic field (Figure 8). The error bars in figures 7 and 8 are 20% of the measured value. This error was estimated by taking a typical experiment and analysing the standard deviation in velocity in a region of maximum velocity. This accounts only for the measurement error, but there are many other factors that are more difficult to quantify and so represents a minimum error. However, in both cases there is a good agreement across all three solutions and the experimental data points.

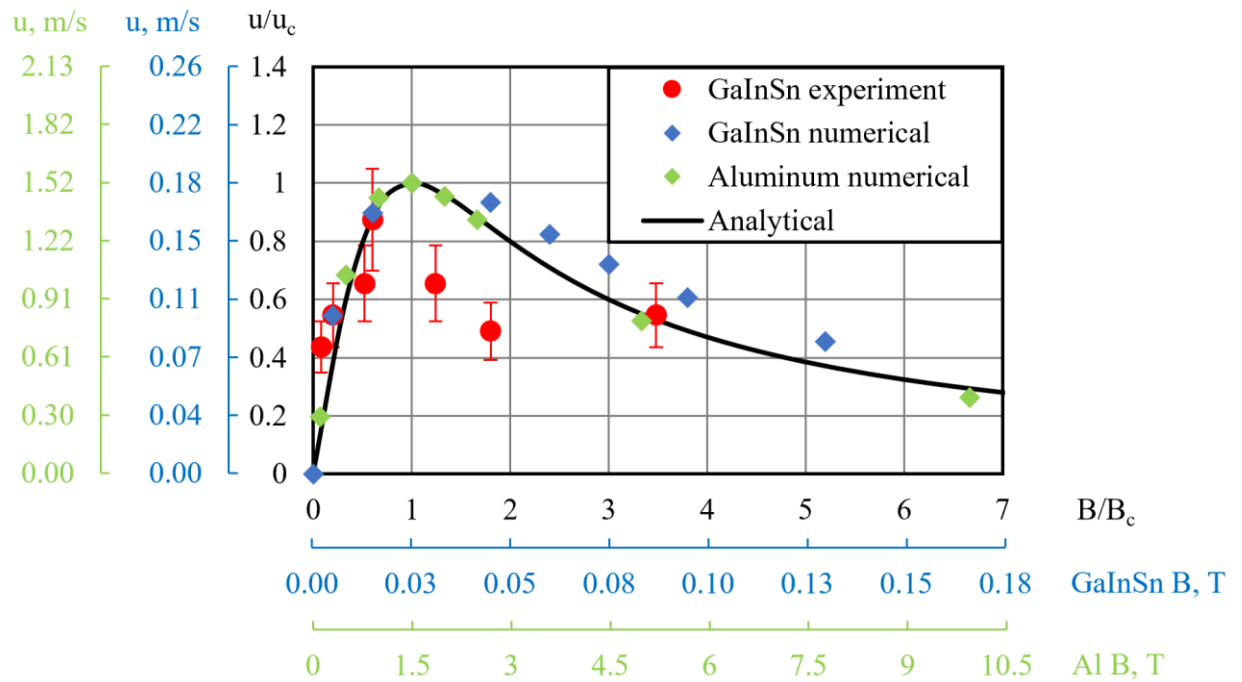


Figure 7. Comparison between the experiment, numerical model and analytical solution for the axial magnetic field case.

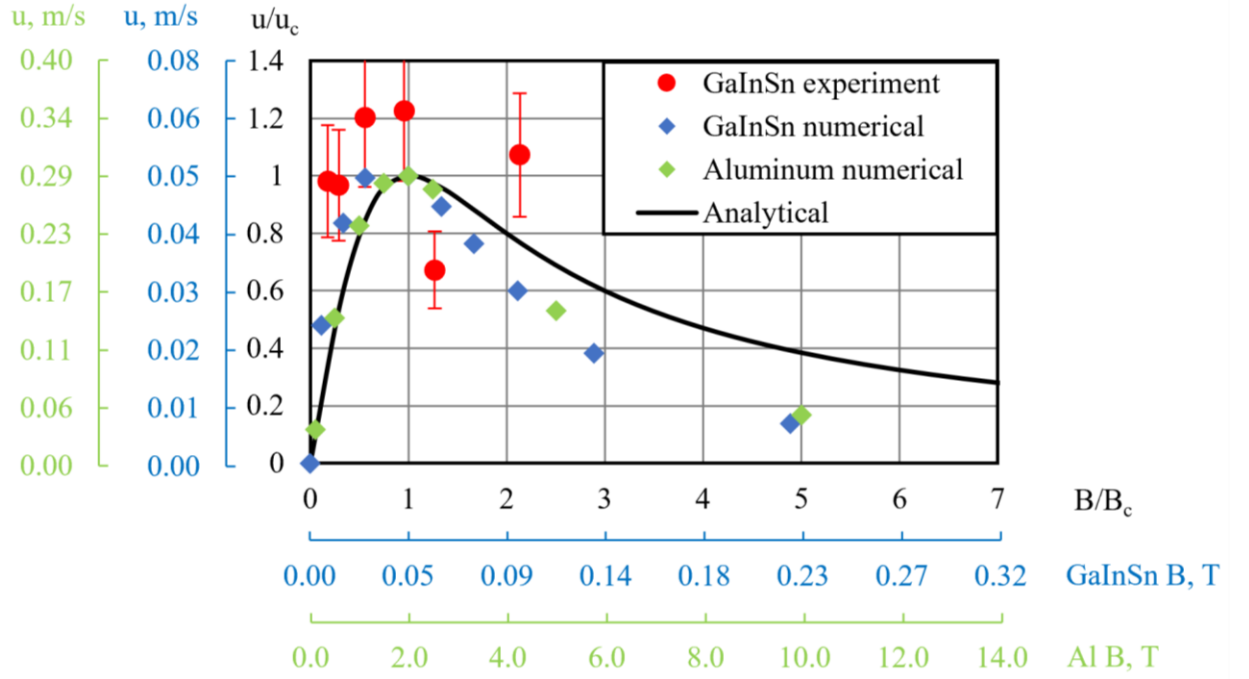


Figure 8. Comparison between the experiment, numerical model and analytical solution for the transverse magnetic field case.

This correlation allows for changes in the bowl experiment to be directly mapped back to an AM process, factoring in changes to length scales, magnetic field intensity, flow velocity and material properties, some that conveniently vanish through scaling. There are essentially three unknowns L , C_E and C_p . In many cases C_E may be estimated by comparing an axial magnetic field to a transverse magnetic field. In an axial case, if the flow is purely angular, a pressure gradient cannot form along the streamlines and $C_p = 0$ and assuming C_E is unchanged between magnetic field orientations yields an additional constraint. Calibration of the analytic solution against bowl experiments and modelling may always be necessary to accurately estimate L and C_E , both of which are dependent on the morphology of the melt pool. However, this approach allows us to explore geometries that are more closely related to the AM process, such as ellipsoid or ‘teardrop’ shapes that occur due to the scanning process via an experiment that can be easily conducted in the lab, e.g. optical measurements with low magnetic fields and using room temperature materials.

CONCLUSION

A scale model experiment accompanied by numerical simulations has been used to study the thermoelectric magnetohydrodynamic phenomena in metal additive manufacturing. A parametric study of magnetic field orientation and magnitude (ranging from 2 mT to 100 mT) for both the Cobalt bowl and the bi-metal bowl was conducted. In the Cobalt bowl, due to the axis symmetry there are only two orientations, axial and transverse, while in the bi-metal bowl there are three orientations, axial, transverse along the bi-metal surface and transverse perpendicular to the bi-metal surface. A good agreement was found between experiments, numerical models and previous similar research with TEMHD flow.

The bi-metal bowl model replicates the case when there are different media at both sides of the melt pool causing asymmetric heat flux and melting. In this case TEMHD flow is more complex and is very different with different magnetic field orientations. The scale model allows us to verify numerical simulations and improve the understanding of TEMHD flow formation and pattern which can be expected during additive manufacturing.

A scaling analysis suggests that the TEMHD effect can be significant in metal additive manufacturing under moderate magnetic field starting from 0.1 T even if differential Seebeck coefficient between solid and liquid phases is as low as 1 $\mu\text{V/K}$. In a small melt pool with extremely high thermal gradient, which occurs during AM, in many cases TEMHD can be the dominant flow even with low magnetic fields. Understanding flows induced in the liquid phase by the applied magnetic field is critical to developing an additional approach to better control liquid metal flow in the melt pool. This could then be used to improve the accuracy of the metal AM for materials and methods that can exploit the TEMHD phenomenon.

These results highlight the intimate coupling between printing strategies of complex geometries and the magnetic field. Processes such as hatching, printing corners, overhangs etc. will all significantly affect the local material properties, thermal field and ultimately thermoelectric currents. These results show that by selecting different orientations of the magnetic field, various complex flows can be generated. In industrial applications, flow can be used to improve print quality and therefore such a control paves the way for a magnetic field strategy to be intimately coupled with scan strategy.

ACKNOWLEDGEMENTS

This work is supported by the Royal Society International Exchange (IES\R2\222050), UK-Latvian Collaboration on Thermoelectric Control of Additive Manufacturing (UKLatTE-AM), the UK Engineering Physical Sciences Research Council “Tailored Microstructures via Thermoelectric-Magnetohydrodynamics for Additive Manufacturing (TEAM)” (EP/W032147/1) and the University of Greenwich “Multi-scale Multi-disciplinary Modelling for Impact” program (M³4Impact) funded by Research England. The authors are grateful for the financial support to University of Latvia development program with big impact project “Improved control of metal 3D printing by thermoelectric magnetohydrodynamics”.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

REFERENCES

1. K. Raghavendra Pai, Vijeesh Vijayan, K. Narayan Prabhu, *Materials today: Proceedings* (2024). <https://doi.org/10.1016/j.matpr.2024.05.008>
2. R.E. Laureijs, J.B. Roca, S.P. Narra, C. Montgomery, J.L. Beuth, E.R. Fuchs, J. *Manuf. Sci. Eng*, 139(8): 081010 (2017). <https://doi.org/10.1115/1.4035420>
3. N.D. Dejene, H.G. Lemu, *Metals*, 13(2), 424 (2023). <https://doi.org/10.3390/met13020424>

4. W. Ji, R. Zhou, P. Vivegananathan, M. S. Wu, H. Gao, K. Zhou, *Progress in Materials Science*, 140, 101194 (2023). <https://doi.org/10.1016/j.pmatsci.2023.101194>
5. J. Wang, R. Zhu, Y. Liu, L. Zhang, *Advanced Powder Materials*, 2(4), 1000137 (2023). <https://doi.org/10.1016/j.apmate.2023.100137>
6. C. Liu, Y. Zhang, N. Banthia, *Additive Manufacturing*, 71, 103606 (2023). <https://doi.org/10.1016/j.addma.2023.103606>
7. D.R. Gunasegaram, A.S. Barnard, M.J. Matthews, B.H. Jared, A.M. Andreaco, K. Bartsch, A.B. Murphy, *Additive Manufacturing*, 81, 104013(2024). <https://doi.org/10.1016/j.addma.2024.104013>
8. A.T. Nesma, M. Simonelli, L. Parry, I. Ashcroft, C. Tuck, R. Hague, *Progress in Materials Science*, 106, 100578 (2019). <https://doi.org/10.1016/j.pmatsci.2019.100578>
9. N.T. Aboulkhair, N.M. Everitt, I. Ashcroft, C. Tuck, *Additive Manufacturing*, 1–4, 77–86 (2014). <https://doi.org/10.1016/j.addma.2014.08.001>
10. R. Montanari, A. Palombi, M. Richetta, A. Varone. 2023, *Metals*, 13 (4), 716 (2023). <https://doi.org/10.3390/met13040716>
11. J.H. Martin, B.D. Yahata, J.M. Hundley, J.A. Mayer, T.A. Schaedler, T.M. Pollock, *Nature*, 549 (7672), 365–369 (2017). [10.1038/nature23894](https://doi.org/10.1038/nature23894)
12. I. Kaldre, Y. Fautrelle, J. Etay, A. Bojarevics, L. Buligins, *Journal of Alloys and Compounds*, 571, 50–55 (2013). <https://doi.org/10.1016/j.jallcom.2013.03.211>
13. C. Zeng, J. Xue, Y. Jia, S. Luo, F. Huang, X. Liu, Y. Du, *Journal of Manufacturing Processes*, 131, 920–946 (2024). <https://doi.org/10.1016/j.jmapro.2024.09.078>
14. I. Kaldre, Y. Fautrelle, J. Etay, A. Bojarevics, L. Buligins, *Journal of Crystal Growth*, 402, 230–233 (2014). <https://doi.org/10.1016/j.jcrysgro.2014.06.029>
15. T. Campanella, C. Charbon, M. Rappaz, *Metallurgical and Materials Transactions A*, 35(10), 3201–3210 (2004). https://doi.org/10.1007/978-3-319-48166-1_18
16. M. Milgrāvis, I. Krastiņš, I. Kaldre, M. Kalvāns, A. Bojarevičs, T. Beinerts, *Crystals*, 13(2), 259 (2023). <https://doi.org/10.3390/cryst13020259>
17. D. Du, L. Wang, A. Dong, W. Yan, G. Zhu, B. Sun, *International Journal of Machine Tools and Manufacture*, 183, 103965 (2022). <https://doi.org/10.1016/j.ijmachtools.2022.103965>
18. R.P. Silva, R. Soares, R. Neto, A. Reis, R. Paiva, R. Madureira, J. Silva, *Materials*, 15(6), 2038 (2022). <https://doi.org/10.3390/ma15062038>
19. N. Gilani, N.T. Aboulkhair, M. Simonelli, M. East, I. Ashcroft, R.J.M. Hague, *Additive Manufacturing*, 48(B), 102402 (2021). <https://doi.org/10.1016/j.addma.2021.1024>
20. P. Kumar, S. Malik, E. Toyserkani, and M. B. Khamesee, *Micromachines*, 13(4), 585 (2022). <https://doi.org/10.3390/mi13040585>
21. X. Fan, T.G. Fleming, D.T. Rees, Y. Huang, S. Marussi, C. L. Leung, R.C. Atwood, A. Kao, P.D. Lee, *Additive Manufacturing*, 71, 103587 (2023). <https://doi.org/10.1016/j.addma.2023.103587>
22. A. Kao, T. Gan, C. Tonry, I. Krastins, K. Pericleous. *Phil. Trans. R. Soc.* 378, 2171 (2020). <https://doi.org/10.1098/rsta.2019.0249>
23. I. Kaldre, Y. Fautrelle, J. Etay, A. Bojarevics and L. Buligins, *Magnetohydrodynamics*, 46(4), 371–380 (2010). <http://doi.org/10.22364/mhd>

24. I. Kaldre, C. Wang, R. Baranovskis, *Magnetohydrodynamics*, 55(4), 469-474 (2019). <http://doi.org/10.22364/mhd>
25. I. Kaldre and V. Felcis, *Magnetohydrodynamics*, 59(3/4), 357-364 (2023). <http://doi.org/10.22364/mhd>
26. A. Kao, C. Tonry, P. Soar, I. Krastins, X. Fan, P.D. Lee, K. Pericleous, *IOP Conf. Ser.: Mater. Sci. Eng*, 1281, 012022 (2023). 10.1088/1757-899X/1281/1/012022
27. X. Fan, T.G. Flemming, S.J. Clark, K. Fezzaa, A.C.M. Getley, S. Marussi, H. Wang, C.L.A. Leung, A. Kao, P.D. Lee, *Science* 387,864-869(2025). <http://doi.org/10.1126/science.ad08554>
28. I. Kaldre, A. Bojarevičs, I. Grants, T. Beinerts, M. Kalvāns, M. Milgrāvis, *Acta Materialia*, 118, 253-259 (2016). <https://doi.org/10.1016/j.actamat.2016.07.045>
29. <https://soft-matter.github.io/trackpy/dev/> (Accessed February 17. 2025) .
30. Yu. Plevachuk, V. Sklyarchuk, S. Eckert, et.al, *Journal of Chemical & Engineering Data* 59(3), 757-763 (2014). [10.1021/je400882q](https://doi.org/10.1021/je400882q)
31. X. Li, Z. Ren, Y. Fautrelle, *Acta Materialia*, 55(11), 3803–3813 (2007). <https://doi.org/10.1016/j.actamat.2007.02.031>