Magnetic modulation of keyhole instability during laser welding and additive manufacturing

Xianqiang Fan^{1,2}*, Tristan G. Fleming³, Samuel J. Clark⁴, Kamel Fezzaa⁴, Anna C. M. Getley^{1,2}, Sebastian Marussi^{1,2}, Hongze Wang^{6,7}, Chu Lun Alex Leung^{1,2}*, Andrew Kao⁵*, Peter D. Lee^{1,2}*

5 Affiliations:

¹Mechanical Engineering, University College London, UK.

²Research Complex at Harwell, Harwell Campus, Didcot, UK.

³Department of Physics, Engineering Physics & Astronomy, Queen's University, Canada.

⁴X-ray Science Division, Argonne National Laboratory, USA.

⁵Computational Science and Engineering Group, Centre for Advanced Simulation and Modelling, University of Greenwich, London, UK.

⁶State Key Laboratory of Metal Matrix Composites, Shanghai Jiao Tong University, China.

⁷School of Materials Science and Engineering, Shanghai Jiao Tong University, Shanghai, China.

15

*Corresponding authors. Peter D. Lee peter.lee@ucl.ac.uk; Xianqiang Fan xianqiang.fan.19@ucl.ac.uk; Andrew Kao a.kao@greenwich.ac.uk; Chu Lun Alex Leung alex.leung@ucl.ac.uk

Keyhole instability during laser welding and laser powder bed fusion (LPBF) can cause keyhole collapse and pore formation. Using high-speed X-ray imaging, we demonstrate that the flow vortex-induced protrusion on the rear keyhole wall is crucial in initiating keyhole instability. Applying a transverse magnetic field suppresses the keyhole instability by driving a secondary thermoelectric magnetohydrodynamics (TEMHD) flow that alters the net flow vortex. This
 minimizes protrusions and large amplitude keyhole oscillations. The suppression effectiveness depends on the laser scanning direction relative to the magnetic field orientation, as this controls the Seebeck effect induced Lorentz force's direction. We show that at LPBF length scales, electromagnetic damping is weak, and for alloys with a large Seebeck coefficient, TEMHD becomes the dominant mechanism controlling flow behind the keyhole.

Additive manufacturing (AM) (1-3) enables efficient and on-demand production of parts with complex geometries and fine details. Laser powder bed fusion is one of the most popular metal AM techniques, repeatedly melting layers of powder into hatched tracks to build complex 3dimensional objects(4). The physics involved in this process is complex, involving melting, vaporisation, rapid solidification, multiple reflections of laser rays, fluid flow, and phase transformations(5). The intense laser heating of metal causes local surface boiling, generating a metal vapor jet(6, 7). The recoil pressure pushes the liquid downward to form a vapor depression zone; if the depression zone is narrow and deep, it is referred to as a keyhole. Pore formation due to keyhole collapse is strongly correlated with keyhole oscillation, e.g., a periodic keyhole oscillation with a frequency of ~43 kHz often precedes a subsequent chaotic and pore-generating turbulence(8). The stochastic formation of large keyhole pores can degrade part qualification and serve as stress concentrators, potentially acting as fatigue initiation sites during component service.

Optimizing process parameters to minimize keyhole pores can only be achieved by using low area energy densities(9), resulting in a narrow and slow build speed process window. The 45 addition of nanoparticles stabilizes keyholes(10), but it adds substantial cost and introduces the risk of altering chemical composition, deviating from the desired material grade. Application of a non-contact external magnetic field mitigates these limitations and promises the potential of modulating keyhole dynamics through electromagnetic forces (11, 12). Specifically, the Seebeck effect, one of the thermoelectric (TE) effects, has drawn increasing attention across various 50 fields, including lithium transport in nuclear fusion(13, 14), immiscible liquid phase separation (15, 16) and flow disruption during solidification in both conventional casting (17, 18)and directed energy deposition (DED)(19). The presence of a high thermal gradient during LPBF is expected to result in substantial thermoelectric currents (TECs) in the melt pool(20). An applied external magnetic field can interact with the TECs, inducing a Lorentz force that may 55 enable precision control over keyhole dynamics.

Gaining a better understanding of potential magnetic field control mechanisms related to the Seebeck effect remains challenging. This is primarily due to the lack of direct observation of keyhole dynamics and melt pool flow during laser melting under the influence of a magnetic field. Previous in situ studies (21, 22) utilized a laser-based illumination source to light up the keyhole with the imaging speed constrained to a few thousand hertz. In these studies, highenergy lasers were applied to generate a weld pool, several hundred times larger than that of a LPBF melt pool.

Magnetic field-enabled mitigation of keyhole porosity

35

40

60

We captured keyhole collapse during laser melting of an AlSi10Mg alloy using high-speed synchrotron X-ray imaging at beamline 32ID of the Advanced Photon Source (USA). The bare substrates (measuring 50 × 10 × 0.8 – 1.1 mm) used here are AlSi10Mg (see materials in the Supplementary). Fig. 1 shows the X-ray imaging system setup for the magnetic field (Fig. 1A, Fig. S1), along with example radiographs acquired (Fig. 1B) with high spatial (2 μm) and temporal (140 kHz) resolutions. When performing zero magnetic field experiments the two ring magnets were removed (see methods in the Supplementary). When the laser scanning direction is from right to left, it is termed as RL and RL-B with a magnetic field applied; for scans from left to right, it is LR and LR-B. The results show a substantial reduction in the total keyhole pore area, by 81%, when a transverse magnetic field of ~0.5 T is applied in the RL-B scan (Fig. 1C, Fig. S2).



Fig. 1. X-ray imaging system, with the two ring magnets to provide a static magnetic field at the laser melting site. (A) A stationary laser beam is implemented to create a stationary melt pool on the substrate's top surface while it is moving. The X-rays pass through the substrate via the ring magnets and are transformed into visible light using a scintillator, which is then captured by the high-speed camera. (B) Captured radiograph and the time-averaged radiograph which allows us to observe keyhole and melt pool boundary. (C) Comparison of total keyhole pore areas between RL and RL-B scans.

80

95

100

Fig. 2 shows a comparison of keyhole dynamics and collapse with and without a magnetic field. During the keyhole collapse process, there are five sequential events and corresponding keyhole morphological changes (Fig. 2A₁-A₅). Keyhole porosity is attributed to keyhole collapse caused by keyhole instability(23–25). Simulations(26) have shown that the rear keyhole wall is, on average, lower temperature than the front, hence has a lower recoil pressure. The weaker recoil pressure makes it more vulnerable to fluctuations and collapse. Therefore, the melt flow behind the rear keyhole wall has a huge impact on keyhole instability(26, 27).

The keyhole collapse process is initiated by the formation of a small protrusion or bulge on the keyhole rear wall (Fig. 2A₁), which reflects the incoming laser beam, heating the keyhole wall unevenly. As a result, the keyhole morphology transforms into an irregular shape (Fig. 2A₂). We hypothesise that the accumulation of recoil pressure in the upper part eventually causes the pressure to breach the narrow section in the middle, and extends all the way down to the bottom, triggering a keyhole expansion. This sudden release of recoil pressure in the upper area results in a rapid change in the shape of the upper keyhole section, forming a thin channel, while the keyhole continues to expand in volume at the bottom (Fig. 2A₃). Following the keyhole expansion process, a rapid keyhole shrinkage occurs in the bottom section, resulting in the formation of a 'J'-shaped keyhole (Fig. 2A₄) that leads to keyhole collapse (Fig. 2A₅) due to the combined effect of melt flow towards the rear keyhole wall (28) and the Plateau-Rayleigh instability (see Supplementary Text 1) which is driven by surface tension (27).

The application of a magnetic field $(0.5 \pm 0.1 \text{ T})$ perpendicular to the scan direction minimizes keyhole porosity for the RL-B scan, reducing the keyhole pore area by 81%. Throughout the process, the keyhole morphology maintains an 'I'-shaped appearance (Fig. 2B₁-B₅, and Movie S1), showing that the magnetic field has made the keyhole more stable. The keyhole behavior and keyhole porosity are independent of the scanning direction with zero magnetic field as shown by the consistent total keyhole pore areas over time. However, this symmetry of the 110 keyhole dynamics with respect to the scanning direction is broken when a magnetic field is applied.



Fig. 2. Comparison of the keyhole morphologies with and without magnetic field. (A1-A5) Keyhole collapse and keyhole pore formation without magnetic field. (**B1-B5**) Typical keyhole morphological evolution in the presence of a magnetic field (See Movie S1). Laser power 225 W, scanning speed 0.5 m/s and laser spot size 47 µm.

The mechanism of magnetic field modulated keyhole instability

115

Fig. 3 shows the mechanistic changes to melt flow along with observations that the magnetic field introduces. For the case where a magnetic field is absent, the schematic of the melt pool 120 flow pattern (Fig. 3A) has two flow cells behind the keyhole in the xz plane (also reported in (29, 30)), and shows the keyhole collapse process (Fig. 3B₁-B₄). The protrusions on the keyhole rear wall, enhanced by the outward Marangoni flow(27, 31, 32) in the middle of the upper melt pool (Fig. 3B₁), intensifies the keyhole fluctuations by redirecting the laser rays. The region underneath the protrusion receives less energy while an intensified laser heating effect occurs in 125 the upper part (caused by reflected laser light from the bottom). This leads to a local recoil pressure drop in the middle of the keyhole, while pressure increases in the upper part. With reduced recoil pressure in the middle section, the surrounding liquid starts filling in the middle part of the keyhole, causing necking (Fig. 3B₂). Simultaneously, the laser beam undergoes multiple reflections at the bottom of the keyhole, vaporizing the metal. This leads to a rapid 130 expansion of the keyhole root, directed towards the rear of the melt pool, which agrees with previous observations(24). Subsequently, the liquid-gas interface of the keyhole contracts at a speed of 5-6 m/s (Fig. $3B_3$), driven by surface tension.

When a magnetic field is applied in $+\hat{y}$ direction (RL-B), the interaction between TECs (see Fig. S3 and Supplementary Text 2) and the magnetic field gives rise to a TE force in the $-\hat{x}$ (backwards) and $+\hat{z}$ (upwards) directions ($J \times B = -J_z B_y \hat{x} + J_x B_y \hat{z}$), resulting in a significant alteration of the flow impacting on keyhole dynamics (Fig. 3C). The TE force is directed towards

the rear of the melt pool, inducing two new flow cells in the xy plane (pink circles in Fig. 3C). As described above, in the zero magnetic field case, the Marangoni flow destabilizes the keyhole by impinging in the mid-upper region of the keyhole rear (stagnation between the two 140 recirculating flows, Fig. 3A) and coupled with the hot fluid reducing surface tension. We hypothesise that for the RL-B case (Fig. 3C-E), the TEMHD flows created by the TE force counteracts the Marangoni recirculation flow in the bulk, reversing the driving force for protrusion formation, stabilizing the keyhole (Fig. 3C). This is supported by the motion of tracer particles added to the substrate that flow upwards and away from the rear of the keyhole (Fig. 145 3E, Movie S2) rather than towards the keyhole (Fig. 3A). TEMHD flows also bring cooler melt from the bottom, further stabilizing the keyhole through increased surface tension, requiring greater free energy to create the extra surface area in a protrusion. These hypotheses are further supported by the change in the melt pool depth. Convective transport of heat causes the melt pool depth to reduce in the upwards flow RL-B case (Fig. 3E and Movie S2), while in the LR-B 150 case the flow is downwards increasing depth (Fig. 3F and Movie S3).

Reversing the scanning direction has the same effect as flipping the magnetic field, i.e., the TE force is reversed. Scanning in the LR direction or $-\hat{x}$, the Lorentz force, $F = I_z B_v(-\hat{x}) + I_z B_v(-\hat{x})$ $J_x B_y(-\hat{z})$, is aligned with the scanning direction $(-\hat{x})$ and downwards $(-\hat{z})$ direction. The melt pool dynamics, including melt pool flow and keyhole behavior, show distinct characteristics 155 when operating in the reversed scanning direction (LR-B) (Fig. 3E and 3F). The \hat{x} -direction Lorentz force is orientated towards the rear keyhole wall, producing two flow cells in the xy plane (Fig. 3G pink circles) with the opposite circulation to the RL-B case (Fig. 3C); these reversed cells assist the formation of protrusions on the keyhole rear wall. Similarly, the vertical cells are reversed (Fig. 3G green circles). Both these cells bring the hot melt from the top surface 160 down along the keyhole, reducing surface tension and making the keyhole less stable and more prone to form a 'J' shape (Fig. 3F) which is susceptible to collapse and keyhole pore formation. Our observations and theoretical understanding (see Supplementary Text 3) are consistent with the results from numerical simulations of AM processes (33-36) and welding (37) that consider the TEMHD. 165

We tracked ten tracer particles along the scanning direction (Fig. S5) to confirm the melt flow direction. Although the flow is three dimensional, the TE force is introduced in the *xz* plane, therefore, the flow information obtained from the *xz* projection (i.e., radiographs) represents the component of the flow driven by the TE force. Keyhole wall perturbations could potentially be caused by Kelvin-Helmholtz instability due to the presence of a fluid velocity gradient across the keyhole wall. However, based on our observations, we believe that protrusion plays a more significant role than the Kelvin-Helmholtz instability in keyhole instability (see Supplementary Text 4).



Fig. 3. Melt pool flow with and without magnetic field. (A) Schematic of melt pool flow pattern in the absence of a magnetic field (laser traversing RL) and (B1-B4) the associated keyhole collapse process. (C) Melt pool flow in the presence of a magnetic field (RL-B). (D1-D3) Schematic of the backward and upward flows, driven by TE force, that maintain an 'I'-shaped keyhole for (C), the RL-B case. (E, F) The W particle trajectories in the RL-B and LR-B scans, show the flow reversal caused by the TE force reversal when the scan direction is reversed. (G) Melt flow pattern when reversing the scanning direction (LR-B case) (See Movies S2 and S3).

Quantification of keyhole oscillation

185

The frequency of keyhole fluctuations was analysed by creating a transient cross-section (tCS) image of the radiographs (see Fig. S6 for methodology); i.e. cross-sections were taken at three positions along the keyhole depth and are presented here as waterfall plots with time (*x*-axis), distance (*y*-axis) and intensity (*z*-axis). From the tCS, keyhole fluctuation frequency and amplitude information could be obtained (Fig. 4 and full-length reconstructed images Fig. S7).

Cross sections at three heights, 1/3, 1/2 and 2/3 of the average keyhole depth, are given in Fig. 4A. Fig. 4B is the reconstructed tCS (detailed in data analysis section in the Supplementary materials), where the bright vertical zone represents the keyhole width. The upper edge of this bright zone corresponds to the rear keyhole wall, while the lower edge represents the front keyhole wall. Therefore, each bright peak in Fig. 4B indicates a keyhole oscillation event at its maximum amplitude i.e. the largest distance between the front and back walls. Using a similar method to (24), we calculated the average peak-to-peak frequency. Two prominent trends
emerge from our analysis of keyhole oscillation. First, near the keyhole aperture (at the 1/3 position), the keyhole has an oscillation frequency of 0.7 kHz and lower amplitudes compared to the region closer to the keyhole bottom (at the 2/3 position), where both the frequency (2.3 kHz) and amplitude are notably higher (Fig. 4C-E). Our observations suggest that the oscillation near

the keyhole bottom contributes most to overall keyhole instability, and hence porosity. Second, it
was observed that the rear wall of the keyhole experiences more pronounced oscillation than the front wall (as indicated by a greater number of peaks in the reconstructed image on the rear wall side, see Fig. 4B). This highlights that the keyhole rear wall plays a large role in determining the overall keyhole instability. This observation contrasts with (9, 38) where they stressed the role of protrusions on the keyhole front wall in leading to keyhole collapse for Ti6Al4V. Due to the
substantial difference in material properties, such as thermal conductivity (90-160 W/(m · K) for AlSi10Mg vs 16-32 W/(m · K) for Ti6Al4V) and viscosity (0.001 Pa · s for AlSi10Mg vs 0.005 Pa · s for Ti6Al4V)(34, 39), the Al alloy might have a different keyhole collapse mechanism. Therefore, we focused our analysis on how rear wall oscillation near the bottom (at the 2/3 position) affects keyhole pore formation.

Under the condition of zero magnetic field at 2/3 depth, the keyhole oscillation exhibits amplitudes ranging from 0 to 90 µm (0 amplitude is defined as the average keyhole width at that position). We classified the oscillation into three intervals to categorize the extent of the amplitude: mild (0 to 30 µm), moderate (30-60 µm), and strong (60-90 µm). The overall keyhole oscillation frequency is 6.1 kHz, which is in agreement with measurements of ~2.5 to ~10 kHz
from prior studies (24, 40, 41). The oscillation frequency is much lower than that in Ti alloy of 16 kHz which could be attributed to the difference in material properties between Al and Ti alloys (see Supplementary Text 5). It decreases with increasing amplitude, specifically, the mild oscillations occur at a rate of 3.7 kHz, the moderate oscillations at 1.7 kHz, and the strong oscillations at 0.7 kHz. A stable keyhole tends to oscillate at a mild level.

The introduction of a magnetic field leads to a substantial reduction in the overall keyhole oscillation frequency (4.6 kHz as compared to 6.1 kHz). At the moderate oscillation level, the frequency reduces by almost 47% to 0.9 kHz, while at the strong oscillation level, it drops by 71% to 0.2 kHz (Fig. 4G). However, the impact of the magnetic field on the frequency of mild oscillation is minimal (less than 6%). We also observed a similar frequency reduction for a laser power of 200 W and scan speed of 0.5 m/s (see Fig. S8), where the keyhole collapse rarely occurs. These findings suggest that with the application of a magnetic field, large oscillations are effectively stabilized, while in the absence of the magnetic field protrusions at the rear wall cause frequent large amplitude (strong and moderate) oscillations.



Fig. 4. Quantification of keyhole oscillation. (A) An image stack capturing keyhole dynamics, blue, green and yellow cross sections are located at the height of 1/3, 1/2 and 2/3 of average keyhole depth, respectively. (B) The transient cross-section (tCS) created by time-slicing the image stack (A), each peak represents a cyclic keyhole oscillation event. (C-E) The tCS at locations of 1/3, 1/2 and 2/3 of the average keyhole depth as depicted in (A). (F) The magnetic counterpart of (E) shows a reconstructed image of the RL-B case. (G) Comparison of keyhole oscillation frequency versus keyhole oscillation amplitude with and without magnetic field. The slanting lines in the reconstructed images represent 'features' from the moving substrate. e.g. once keyhole pore is trapped in the solid it becomes static to the substrate and manifests as a bright slanting strip (moving in both time and along cross-section) in (E).

240

245

250

255

Melt pool dynamics with opposing scanning directions

To better understand the dependence of keyhole dynamics on the laser scanning direction when a magnetic field is applied, we carried out laser melting experiments on a high silicon Al alloy, AlSi7Mg. We conducted our paired experiments on the same substrate to ensure identical experimental conditions, with the sole variation being the scanning direction.

We found a large contrast in the keyhole behavior and keyhole porosity formed between the RL-B and LR-B scans (Fig. 5, Movie S4). The RL-B scan produced a relatively stable 'I'-shaped keyhole with minimal changes in shape over time (Fig. 5A₁-A₄), and only small keyhole pores were produced (Fig. 5C). In contrast, the LR-B scan exhibited a cyclic 'I'-'J' keyhole transformation, accompanied by large amplitude keyhole oscillations (Fig. 5B₁-B₄), resulting in the formation of large pores (Fig. 5D). The RL-B scan had 83% less porosity than the LR-B scan (Fig. 5E), demonstrating the importance of the Seebeck effect for high silicon content aluminum alloys. The average equivalent pore diameter increased by 144% going from the RL-B to LR-B scan (9 μ m to 22 μ m). Likewise, the average keyhole width increased by 31% from 32 μ m in the RL-B scan to 42 μ m in the LR-B scan, due to the enhanced keyhole oscillation in the LR-B scan. It was observed that under LR-B scan conditions, the application of a magnetic field has the effect of stretching the keyhole, i.e., the keyhole depth increases and strongly fluctuates. A deeper keyhole increases the chance of the keyhole tip contacting the melt pool bottom and being trapped by the advancing solidification front (Fig. S9). Additionally, we found that inclination of the front keyhole wall does not seem to change under the conditions of RL-B and LR-B scans. The observed phenomena, such as changes in keyhole width and depth, can be attributed to changes in flow.

Reversing the scanning direction also has an impact on the melt pool depth. In the absence of a magnetic field, we found that the melt pool depth is consistent and independent of the scanning direction (Fig. S10). However, when a magnetic field is applied, the melt pool depth becomes contingent on the scanning direction, resulting in a noticeably deeper melt pool during the LR-B scan (Fig. S4). This observation agrees with high-fidelity computational findings (*35*), where melt pool depth was predicted to strongly depend on the orientation of the magnetic field relative to scan direction. I.e. bi-directional scanning in the presence of a magnetic field led to the formation of an alternating thin and thick layered structure.

The changes in keyhole and melt pool behavior observed with opposite scanning directions can be explained by variations in melt pool flow driven by the TE forces, as the TE force is the only force whose direction depends on the scanning direction. In the RL-B scan, the TE force is directed upwards and towards the back of the pool (see black arrow in Fig. 5A₁), generating flow vortices as depicted in Fig. 3C. Conversely, in the LR-B scan, the TE force is directed downwards and towards the front of the pool (see black arrow in Fig. 5B₁), reversing the flow vortices (Fig. 3G). This reversal helps propel the hot melt flow downwards, deepening the melt pool. Reversing the scan direction (LR-B scan), the TE force-induced flow is directed towards the front of the pool, enhancing protrusion formation, resulting in a more fluctuating, deeper, and wider keyhole, on average.

280

260

265

270



Fig. 5. Keyhole dynamics and pore formation of AlSi7Mg with a reversed laser scanning direction in the presence of a magnetic field. (A1-A4) show typical keyhole morphology evolution with scanning direction from right to left (RL-B). (B1-B4) The scanning direction is left to right (LR-B). (C) and (D) show the pore distribution along the tracks for the RL-B and LR-B cases, respectively. (E) Comparison of total keyhole pore areas for the two opposite scanning directions with a magnetic field applied (see Movie S4).

Discussion

We estimate that the TE and Marangoni forces are around 7-18% of surface tension and recoil pressure (see Supplementary Text 6). These values are reasonable, because if the TE or Marangoni forces were on the scale of surface tension or recoil pressure, then the keyhole would be massively deformed rather than just perturbed. Surface tension also acts against recoil pressure and so the difference between them determines the perturbation. Marangoni forces assist surface tension, while the TE force will either assist recoil pressure or surface tension depending on the sign of the magnetic field. Simply put, for stability the TEMHD should act against Marangoni forces to mitigate the perturbing force.

In this work the TE force dominates over the traditional electromagnetic damping (EMD) force that acts as a breaking force on fluid motion. This is observed in the breaking of symmetry between scan directions in melt pool and keyhole dynamics. EMD has been attributed to stabilizing keyholes in prior studies using welding conditions (11, 12); however, the contrasting behavior in our study using LPBF conditions to prior work is due to two key differences: Seebeck coefficient, *S* (up to two orders larger in our work), and length scale, *L* (one order smaller in our work), which also affects the thermal gradient, $|\nabla T| \approx \Delta T/L$. We determine the dominant mechanism by taking relative forces and using dimensionless analysis. I.e., the scaling behavior can be approximated by taking ratios of the EMD force to Marangoni force

285

295

290

305

 $\left(\frac{|F_{EMD}|}{|F_{Ma}|} = \frac{\sigma |u|B^2 L^2}{\gamma' |\nabla T|}\right)$ and the TE force to Marangoni force $\left(\frac{|F_{TE}|}{|F_{Ma}|} = \frac{\sigma S|B|L}{\gamma'}\right)$. In table S3, we list the material properties, the scale of the melt pool and the calculated dimensionless numbers for our study and prior welding studies (11, 37, 42, 43). Assuming all other properties are the same (e.g. our work and (11)), $\frac{|F_{TE}|}{|F_{Ma}|}$ scales as L^2 and so in our work EMD will be two orders of magnitude smaller than that in (11), while $\frac{F_{TE}}{F_{Ma}}$ scales as the product *SL* and so the TE force will be one order 310 of magnitude larger. At the length scales of LPBF, this dimensionless analysis shows that changing alloy composition to increase S (e.g. by adding silicon to aluminum alloys) is a viable mechanism without significantly increasing the magnetic field, $(|\mathbf{B}| \gg 1 \text{ T into the range of } \mathbf{B})$ super conducting magnets). A detailed analysis is provided in Supplementary Text 7. Existing literature that explores the Seebeck effect(34, 36, 44, 45) typically performs 315 experiments or modelling using high silicon Al alloys. As evidenced in directional solidification (18), a higher silicon concentration in aluminum alloys demonstrates a strong Seebeck effect, and hence they hypothesise Si increases the Seebeck coefficient of the alloy. To test the influence of silicon content on the Seebeck effect, experiments were conducted with an Al6061 alloy which has a negligible silicon content. The melt pool depth remained unchanged when 320 reversing the scanning direction (195 μm , see Figs. S11A and 11B) when the magnetic field is present. This observation is in direct contrast to the AlSi7Mg alloy where we observed 230 µm melt pool depth for the left to right scan and 210 µm for the reversed scan (Figs. S11C and 11D). This indicates that the Seebeck effect in Al6061 alloy is significantly reduced compared to AlSi7Mg. 325

Conclusions

By performing high-speed synchrotron X-ray imaging in the frame of reference of the laser beam, we demonstrated that the protrusion formation on the keyhole rear wall, driven by melt flow, initiates instability leading to keyhole collapse. Through the application of a 0.5 + 0.1 T magnetic field during the laser melting of high silicon aluminum alloys (e.g. AlSi10Mg), with a 330 right to left scan (RL-B), we achieved an 81% reduction in keyhole porosity. This reduction stemmed from the magnetic field altering melt flow owing to the Seebeck effect, thereby suppressing the formation of protrusions on the keyhole rear wall which predominantly causes the large amplitude keyhole oscillation. We revealed that the direction of the Seebeck effect induced-Lorentz force is dependent on the laser scanning direction relative to the magnetic field 335 orientation, hence the protrusion suppression is only effective in the RL-B scan conditions, e.g., the keyhole foot is minimized in the RL-B scan while enhanced in the LR-B scan. Our dimensionless analysis shows that stabilizing keyhole oscillations with electromagnetic damping (EMD) is not feasible in LPBF under low magnetic field conditions (< 1 T), but increasing Seebeck power (e.g. by increasing silicon content) activates TE forces creating a viable 340 stabilization mechanism. This work resolves long-standing conflicting theories on the impact of static magnetic fields on weld pool dynamics, showing that in LPBF, with scales much smaller than in welding, TE forces primarily govern melt pool flow, stabilizing the keyhole and preventing porosity. We encapsulate our observations using dimensionless ratios of forces to guide the application of magnetic control over a range of AM and welding processes, including 345 variations of processing parameters and materials where the Seebeck effect is expected to be large, such as functionally graded materials, bimetallic materials, composites, dual-phase materials, and other materials.

350 **References and Notes**

- 1. D. Gu, X. Shi, R. Poprawe, D. L. Bourell, R. Setchi, J. Zhu, Material-structureperformance integrated laser-metal additive manufacturing. *Science (80-.).* **372** (2021), doi:10.1126/science.abg1487.
- 2. C. Panwisawas, Y. T. Tang, R. C. Reed, Metal 3D printing as a disruptive technology for superalloys. *Nat. Commun.* **11** (2020), p. 2327.
- 3. J. Zhang, M. J. Bermingham, J. Otte, Y. Liu, Z. Hou, N. Yang, Y. Yin, M. Bayat, W. Lin, X. Huang, D. H. StJohn, M. S. Dargusch, Ultrauniform, strong, and ductile 3D-printed titanium alloy through bifunctional alloy design. *Science* (80-.). **383**, 639–645 (2024).
- 4. T. DebRoy, H. L. Wei, J. S. Zuback, T. Mukherjee, J. W. Elmer, J. O. Milewski, A. M. Beese, A. Wilson-Heid, A. De, W. Zhang, Additive manufacturing of metallic components Process, structure and properties. *Prog. Mater. Sci.* **92**, 112–224 (2018).
 - 5. C. Zhao, B. Shi, S. Chen, D. Du, T. Sun, B. J. Simonds, K. Fezzaa, A. D. Rollett, Laser melting modes in metal powder bed fusion additive manufacturing. *Rev. Mod. Phys.* **94**, 45002 (2022).
- I. Bitharas, N. Parab, C. Zhao, T. Sun, A. D. Rollett, A. J. Moore, The interplay between vapour, liquid, and solid phases in laser powder bed fusion. *Nat. Commun.* 13, 1–12 (2022).
 - 7. J. Liu, P. Wen, Metal vaporization and its influence during laser powder bed fusion process. *Mater. Des.* **215**, 110505 (2022).
 - 8. S. A. Khairallah, T. Sun, B. J. Simonds, Onset of periodic oscillations as a precursor of a transition to pore-generating turbulence in laser melting. *Addit. Manuf. Lett.* **1**, 100002 (2021).
 - 9. C. Zhao, N. D. Parab, X. Li, K. Fezzaa, W. Tan, A. D. Rollett, T. Sun, Critical instability at moving keyhole tip generates porosity in laser melting. *Science (80-.).* **1086**, 1080–1086 (2020).
 - M. Qu, Q. Guo, L. I. Escano, A. Nabaa, S. M. H. Hojjatzadeh, Z. A. Young, L. Chen, Controlling process instability for defect lean metal additive manufacturing. *Nat. Commun.* 13, 1–8 (2022).
 - 11. F. Liu, H. Wang, X. Meng, C. Tan, B. Chen, X. Song, Effect of magnetic field orientation on suppressing porosity in steady-magnetic-field-assisted aluminum alloy deeppenetration laser welding. *J. Mater. Process. Technol.* **304**, 117569 (2022).
 - 12. X. Meng, M. Bachmann, A. Artinov, M. Rethmeier, A study of the magnetohydrodynamic effect on keyhole dynamics and defect mitigation in laser beam welding. *J. Mater. Process. Technol.* **307**, 117636 (2022).
- G. G. Van Eden, V. Kvon, M. C. M. Van De Sanden, T. W. Morgan, Oscillatory vapour shielding of liquid metal walls in nuclear fusion devices. *Nat. Commun.* 8 (2017), doi:10.1038/s41467-017-00288-y.
 - M. A. Jaworski, T. K. Gray, M. Antonelli, J. J. Kim, C. Y. Lau, M. B. Lee, M. J. Neumann, W. Xu, D. N. Ruzic, Thermoelectric magnetohydrodynamic stirring of liquid metals. *Phys. Rev. Lett.* **104**, 1–4 (2010).

360

370

375

380

	15.	Y. Zhong, T. Zheng, L. Dong, B. Zhou, W. Ren, J. Wang, Z. Ren, F. Debray, E. Beaugnon, H. Wang, Q. Wang, Y. Dai, Controlling droplet distribution using thermoelectric magnetic forces during bulk solidification processing of a Zn-6 wt.%Bi immiscible alloy. <i>Mater. Des.</i> 100 , 168–174 (2016).
395	16.	M. Li, T. Tamura, Influence of static magnetic field intensity on the separation and migration of Fe-rich bulks in an immiscible ($Fe - C$) – Cu alloy. <i>Philos. Mag.</i> 6435 (2019), doi:10.1080/14786435.2019.1616122.
400	17.	X. Fan, N. Shevchenko, C. Tonry, S. J. Clark, R. C. Atwood, S. Eckert, K. Pericleous, P. D. Lee, A. Kao, Controlling solute channel formation using magnetic fields. <i>Acta Mater.</i> 256 , 119107 (2023).
	18.	B. Cai, A. Kao, E. Boller, O. V. Magdysyuk, R. C. Atwood, N. T. Vo, K. Pericleous, P. D. Lee, Revealing the mechanisms by which magneto-hydrodynamics disrupts solidification microstructures. <i>Acta Mater.</i> 196 , 200–209 (2020).
405	19.	X. Fan, T. G. Fleming, D. T. Rees, Y. Huang, S. Marussi, C. Lun, A. Leung, R. C. Atwood, A. Kao, P. D. Lee, Thermoelectric magnetohydrodynamic control of melt pool flow during laser directed energy deposition additive manufacturing. <i>Addit. Manuf.</i> 71 , 103587 (2023).
410	20.	S. M. H. Hojjatzadeh, N. D. Parab, W. Yan, Q. Guo, L. Xiong, C. Zhao, M. Qu, L. I. Escano, X. Xiao, K. Fezzaa, W. Everhart, T. Sun, L. Chen, Pore elimination mechanisms during 3D printing of metals. <i>Nat. Commun.</i> 10 , 1–8 (2019).
	21.	M. Li, J. Xu, Y. Huang, Y. Rong, Improving Keyhole Stability by External Magnetic Field in Full Penetration Laser Welding. <i>Jom.</i> 70 , 1261–1266 (2018).
415	22.	Ö. Üstündağ, N. Bakir, A. Gumenyuk, M. Rethmeier, Influence of oscillating magnetic field on the keyhole stability in deep penetration laser beam welding. <i>Opt. Laser Technol.</i> 135 (2021), doi:10.1016/j.optlastec.2020.106715.
	23.	Z. Gan, O. L. Kafka, N. Parab, C. Zhao, L. Fang, O. Heinonen, T. Sun, W. K. Liu, Universal scaling laws of keyhole stability and porosity in 3D printing of metals. <i>Nat. Commun.</i> 12 (2021), doi:10.1038/s41467-021-22704-0.
420	24.	Y. Huang, T. G. Fleming, S. J. Clark, S. Marussi, K. Fezzaa, J. Thiyagalingam, C. L. A. Leung, P. D. Lee, Keyhole fluctuation and pore formation mechanisms during laser powder bed fusion additive manufacturing. <i>Nat. Commun.</i> 13 , 1–11 (2022).
	25.	Z. Ren, L. Gao, S. J. Clark, K. Fezzaa, P. Shevchenko, A. Choi, W. Everhart, A. D. Rollett, L. Chen, T. Sun, Machine learning-aided real-time detection of keyhole pore generation in laser powder bed fusion. <i>Science (80)</i> . 379 , 89–94 (2023).
425	26.	L. Wang, Y. Zhang, H. Y. Chia, W. Yan, Mechanism of keyhole pore formation in metal additive manufacturing. <i>npj Comput. Mater.</i> 8 (2022), doi:10.1038/s41524-022-00699-6.
	27.	R. Lin, H. ping Wang, F. Lu, J. Solomon, B. E. Carlson, Numerical study of keyhole dynamics and keyhole-induced porosity formation in remote laser welding of Al alloys. <i>Int. J. Heat Mass Transf.</i> 108 , 244–256 (2017).
430	28.	T. Yu, J. Zhao, Quantifying the mechanisms of keyhole pore evolutions and the role of metal-vapor condensation in laser powder bed fusion. <i>Addit. Manuf.</i> 72 , 103642 (2023).

- 29. N. Kouraytem, X. Li, R. Cunningham, C. Zhao, N. Parab, T. Sun, A. D. Rollett, A. D. Spear, W. Tan, Effect of Laser-Matter Interaction on Molten Pool Flow and Keyhole Dynamics. *Phys. Rev. Appl.* **11**, 1 (2019).
- Q. Guo, M. Qu, L. I. Escano, S. M. H. Hojjatzadeh, Z. Young, K. Fezzaa, L. Chen, Revealing melt flow instabilities in laser powder bed fusion additive manufacturing of aluminum alloy via in-situ high-speed X-ray imaging. *Int. J. Mach. Tools Manuf.* 175, 103861 (2022).
 - 31. Q. Guo, C. Zhao, M. Qu, L. Xiong, S. M. H. Hojjatzadeh, L. I. Escano, N. D. Parab, K. Fezzaa, T. Sun, L. Chen, In-situ full-field mapping of melt flow dynamics in laser metal additive manufacturing. *Addit. Manuf.* **31**, 100939 (2020).
 - L. Aucott, H. Dong, W. Mirihanage, R. Atwood, A. Kidess, S. Gao, S. Wen, J. Marsden, S. Feng, M. Tong, T. Connolley, M. Drakopoulos, C. R. Kleijn, I. M. Richardson, D. J. Browne, R. H. Mathiesen, H. V. Atkinson, Revealing internal flow behaviour in arc welding and additive manufacturing of metals. *Nat. Commun.* 9, 1–7 (2018).
 - 33. A. Kao, T. Gan, C. Tonry, I. Krastins, K. Pericleous, Study of thermoelectric magnetohydrodynamic convection on solute redistribution during laser additive manufacturing. *IOP Conf. Ser. Mater. Sci. Eng.* **861** (2020), doi:10.1088/1757-899X/861/1/012009.
- 450 34. A. Kao, T. Gan, C. Tonry, I. Krastins, K. Pericleous, Thermoelectric magnetohydrodynamic control of melt pool dynamics and microstructure evolution in additive manufacturing. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* **378**, 20190249 (2020).
 - 35. A. Kao, C. Tonry, P. Soar, I. Krastins, X. Fan, P. Lee, K. Pericleous, Modulating Meltpool Dynamics and Microstructure using Thermoelectric Magnetohydrodynamics in Additive Manufacturing. *IOP Conf. Ser. Mater. Sci. Eng.* **1281**, 012022 (2023).
 - 36. L. Wang, W. Yan, Thermoelectric Magnetohydrodynamic Model for Laser-Based Metal Additive Manufacturing. *Phys. Rev. Appl.* **15**, 1 (2021).
 - 37. M. Kern, P. Berger, H. Hügel, Magneto-Fluid Dynamic Control of Seam Quality in CO2 Laser Beam Welding. *Weld. J.* **79**, 72–78 (2000).
 - 38. C. Zhao, Q. Guo, X. Li, N. Parab, K. Fezzaa, W. Tan, L. Chen, T. Sun, Bulk-Explosion-Induced Metal Spattering during Laser Processing. *Phys. Rev. X.* 9, 21052 (2019).
 - 39. L. Wang, Y. Zhang, W. Yan, Evaporation Model for Keyhole Dynamics during Additive Manufacturing of Metal. *Phys. Rev. Appl.* **14**, 1 (2020).
 - 40. D. Farson, K. Hillsley, J. Sames, R. Young, Frequency-time characteristics of air-borne signals from laser welds. **42**, 86–94 (2018).
 - 41. S. Ao, Z. Luo, M. Feng, F. Yan, Simulation and experimental analysis of acoustic signal characteristics in laser welding. *Int. J. Adv. Manuf. Technol.* **81**, 277–287 (2015).
 - 42. G. Ambrosy, P. Berger, H. Huegel, D. Lindenau, Improvement of laser beam welding by electromagnetic forces in the weld pool. *First Int. Symp. High-Power Laser Macroprocessing.* **4831**, 175 (2003).
 - 43. L. Cao, Q. Zhou, H. Liu, J. Li, S. Wang, Mechanism investigation of the influence of the

14

460

455

440

445

470

magnetic field on the molten pool behavior during laser welding of aluminum alloy. Int. J. Heat Mass Transf. 162, 120390 (2020).

- 44. D. Du, J. C. Haley, A. Dong, Y. Fautrelle, D. Shu, G. Zhu, X. Li, B. Sun, E. J. Lavernia, 475 Influence of static magnetic field on microstructure and mechanical behavior of selective laser melted AlSi10Mg alloy. Mater. Des. 181, 107923 (2019).
 - D. Du, L. Wang, A. Dong, W. Yan, G. Zhu, B. Sun, Promoting the densification and grain 45. refinement with assistance of static magnetic field in laser powder bed fusion. Int. J. Mach. Tools Manuf. 183, 103965 (2022).
 - C. L. A. Leung, S. Marussi, M. Towrie, J. del Val Garcia, R. C. Atwood, A. J. Bodey, J. 46. R. Jones, P. J. Withers, P. D. Lee, Laser-matter interactions in additive manufacturing of stainless steel SS316L and 13-93 bioactive glass revealed by in situ X-ray imaging. Addit. Manuf. 24, 647-657 (2018).
- 47. C. Zhao, K. Fezzaa, R. W. Cunningham, H. Wen, F. De Carlo, L. Chen, A. D. Rollett, T. 485 Sun, Real-time monitoring of laser powder bed fusion process using high-speed X-ray imaging and diffraction. Sci. Rep. 7, 1–11 (2017).
 - 48. N. D. Parab, C. Zhao, R. Cunningham, L. I. Escano, K. Fezzaa, W. Everhart, A. D. Rollett, L. Chen, T. Sun, Ultrafast X-ray imaging of laser-metal additive manufacturing processes. J. Synchrotron Radiat. 25, 1467–1477 (2018).
 - 49. T. G. Fleming, S. J. Clark, X. Fan, K. Fezzaa, C. L. A. Leung, P. D. Lee, J. M. Fraser, Synchrotron validation of inline coherent imaging for tracking laser keyhole depth. Addit. Manuf. 77, 103798 (2023).
 - 50. R. Cunningham, C. Zhao, N. Parab, C. Kantzos, J. Pauza, K. Fezzaa, T. Sun, A. D. Rollett, Keyhole threshold and morphology in laser melting revealed by ultrahigh-speed xray imaging. Science (80-.). 363, 849-852 (2019).
 - 51. L. Huang, X. Hua, D. Wu, F. Li, Numerical study of keyhole instability and porosity formation mechanism in laser welding of aluminum alloy and steel. J. Mater. Process. Technol. 252, 421-431 (2018).
- J. McCuan, Retardation of Plateau-Rayleigh Instability: A Distinguishing Characteristic 52. 500 Among Perfectly Wetting Fluids. 1, 1–6 (1997).
 - 53. H. Werheit, U. Kuhlmann, B. Herstell, W. Winkelbauer, Reliable measurement of Seebeck coefficient in semiconductors. J. Phys. Conf. Ser. 176, 0-5 (2009).

J. Gao, M. Han, A. Kao, K. Pericleous, D. V. Alexandrov, P. K. Galenko, Dendritic 54. growth velocities in an undercooled melt of pure nickel under static magnetic fields: A test of theory with convection. Acta Mater. 103 (2016), pp. 184–191.

- J. Chen, Y. Wei, X. Zhan, C. Gu, X. Zhao, Thermoelectric currents and thermoelectric-55. magnetic effects in full-penetration laser beam welding of aluminum alloy with magnetic field support. Int. J. Heat Mass Transf. 127, 332-344 (2018).
- 56. P. G. Drazin, Dynamical Meteorology: Kelvin-Helmholtz Instability. Encycl. Atmos. Sci. Second Ed. 3, 343–346 (2015).
 - 57. C. L. A. Leung, D. Luczyniec, E. Guo, S. Marussi, R. C. Atwood, M. Meisnar, B. Saunders, P. D. Lee, Quantification of Interdependent Dynamics during Laser Additive

490

495

480

505

Manufacturing Using X-Ray Imaging Informed Multi-Physics and Multiphase Simulation. *Adv. Sci.* **2203546**, 1–15 (2022).

58. M. Poletto, D. D. Joseph, Effective density and viscosity of a suspension. *J. Rheol. (N. Y. N. Y).* **39**, 323–343 (1995).

Acknowledgements: All authors are grateful for the use of the facilities provided at APS and
 thank APS for providing the beamtime (GUP-73825) and staff in beamline ID32 for the technical assistance. This research used resources of the Advanced Photon Source, a U.S. Department of Energy (DOE) Office of Science user facility operated for the DOE Office of Science by Argonne National Laboratory under Contract No. DE-AC02-06CH11357. CLAL is funded by IPG Photonics/ Royal Academy of Engineering Senior Research Fellowship in SEARCH (ref:
 RCSRF2324-18-71) and EP/W037483/1. HW acknowledges the financial supports of National Key Research and Development Program of China (No. 2024YFE0105700) and National Natural Science Foundation of China (52075327).

Funding: This research was supported under:

UK-EPSRC grants (EP/W031167/1, EP/W032147/1, EP/W006774/1, EP/P006566/1, EP/W003333/1, and EP/V061798/1)

MAPP: EPSRC Future Manufacturing Hub in Manufacture using Advanced Powder Processes (EP/P00 656 6/1)

Royal Academy of Engineering Chair in Emerging Technologies (CiET1819/10)

Author contributions:

515

530

535	Conceptualization: P.D.L., X.F. and A.K.
	Methodology: T.G.F., X.F., S.M. and H.W.
	Investigation: T.G.F., S.J.C., K.F., A.C.M.G. and X.F.
	Visualization: T.G.F., S.J.C., K.F., A.C.M.G. and X.F.
	Funding acquisition: P.D.L., C.L.A.L., and A.K.
540	Project administration: P.D.L. and A.K.
	Supervision: P.D.L. and A.K.
	Writing – original draft: X.F.
	Writing – review & editing: X.F., T.G.F., S.J.C., K. F., A.C.M. G., S.M., H.W, C.L.A.L. A.K. and P.D.L.
545	
	Competing interests: Authors declare that they have no competing interests.
	Deter and metericle and the little All data and and the in the mean solution the

Data and materials availability: All data are available in the manuscript or the supplementary material.

Supplementary Materials

550 Materials and Methods

Supplementary Text Figs. S1 to S11 Tables S1 to S3 Captions for Movies S1 to S4 References (44-58) Movies S1 to S4

Materials and Methods

590 Materials

595

600

605

There are two types of samples: bare substrates and single-layer powder bed samples. The bare substrates (measuring $50 \times 10 \times 0.8 - 1.1$ mm), include AlSi10Mg, AlSi7Mg (laboratory casted, supplied by Shanghai Jiao Tong University, SJTU), and Al6061 alloy (McMaster-Carr, cold-rolled), all cut using electrical discharge machining. The composition details are listed in Table S1. The substrate surface was polished using 1000-grit sandpapers. The single-layer powder bed sample comprises an AlSi10Mg substrate and a thin layer of AlSi10Mg powder (laboratory gas atomized, supplied by SJTU), ~120 µm thick, with an average powder diameter of 30 µm. These were sandwiched between two pieces of glassy carbon plates. Tungsten particles, with an average diameter of 15 µm (~0.2 vol.%), were used to trace the melt pool flow.

Aluminum has a relatively low viscosity for metals, whereas titanium and nickel alloys can be up to five times more viscous. Alloys with a higher viscosity can stabilize the keyhole and minimize keyhole porosity (10). A higher viscosity melt can also stabilize the melt pool and minimize spattering (46). We choose Al as the worst-case scenario for pore formation to demonstrate the effect of magnetic field on stabilizing keyhole.

Methods

High-speed synchrotron X-ray imaging:

The LPBF experiments were performed using a linear motion stage (Parker MX80L, USA) integrated into the laser powder bed fusion process replicator at the Advanced Photon Source (APS) (47, 48). The laser is kept stationary while the stage moves horizontally perpendicular to the X-ray beam. Experiments were performed using both bare substrates and powder. To apply the magnetic field, two permanent NdFeB ring magnets were positioned with an 8 mm gap between them to accommodate the substrate. The magnets were orientated perpendicular to the laser scan direction, and remained fixed in place, thereby establishing a consistent magnetic field in the melt pool location. The magnetic field had a flux density, measured using a Gaussmeter, of 0.5 ± 0.1 T at the top surface of the substrate. The use of ring magnets allows the X-ray beam to pass through the magnet system and substrate, enabling the high-speed camera to capture the melt pool dynamics.

High-speed, high-resolution, X-ray imaging was performed using an in-house LPBF test rig developed at 32-ID, APS (48). This setup enabled us to capture the laser melting process and investigate the impact of the magnetic field on keyhole dynamics. A continuous wave ytterbium fibre laser (1070 nm wavelength) was employed to conduct single-track laser melting. The laser powers were set to 200 W and 225 W, with a constant stage traverse speed of $0.51 \pm 0.06 m/s$, and a $47 \pm 2 \mu m$ laser spot size (1/e², with gaussian profile) at the substrate surface (49) (see Table S2 for the in situ experiment list). During the laser melting process, X-rays passed through the sample and were converted to visible light by a scintillator, before being captured by a Photron FastCam SA-Z 2100 K (Photron Inc., Tokyo, Japan) high-speed camera at a framerate of 140 kHz with an exposure time of 0.6 µs, and pixel size of 2 µm.

To ensure that the melt pool remains static with respect to the magnetic field, we kept the laser beam and magnet stationary while the substrate moves transversely using a linear motion stage. This approach allows for equivalent laser scanning conditions while minimizing the required camera memory by using a reduced field of view, enabling a longer recording time and therefore collecting more data to confirm our hypotheses. By using this approach, we increased the imaging time of the APS system from 2 ms (280 frames, 1 mm track length) (9, 50) to 17 ms (2400 frames, 8.5 mm track length) at a frame rate of 140 kHz and scan speed of 0.5 m/s. This allowed us to repeatedly observe the mechanism of keyhole collapse, specifically the collapse of the rear keyhole wall, which had previously been hypothesized in simulations (27, 51). Previous investigations(9, 38, 50) on keyhole collapse mechanisms have described the phenomena as occurring on a rather short time scale, i.e. within 4 μ s, capturing the process of 'J'-shaped keyholes to keyhole collapse, using megahertz X-ray imaging. In this study, we captured the underlying mechanisms across multiple timescales. This includes the short-timescale (~4 μ s) of keyhole collapse, the long-timescale (~40 μ s) of instability initiation and transformation from 'I' to 'J' shape keyhole prior to collapse, and multiple repeating events (~1 ms), all within a single experiment at comparatively large time scales (~17 ms).

Tungsten particles were used as flow tracers to characterize the melt flow within the melt 645 pool. The addition of tungsten tracers has negligible effect on melt viscosity (see Supplementary Text 8). The tungsten particles were spread on the top surface of the substrate, followed by laser scanning across the top surface of the substrate to embed the tungsten particles. Following that we spread a layer of AliSi10Mg powder on the top of the substrate for the LPBF processing. The powder layer can increase the laser absorptivity thus better wetting the tungsten particles to 650 incorporate the particles into the melt pool. Although there is an unavoidable small variation in powder layer thickness that may slightly affect the flow, we believe it does not change the direction of flow which is the key information needed to obtain from tracing particles. During the LPBF process, as the laser scans across, a melt pool is formed from the liquidation of the powder and substrate, but the high melting-point tungsten particles remain as solid particles incorporated 655 into the melt pool, enabling us to trace the flow (Movies S2 and S3). To better visualize the flow, the trajectories of the tungsten particles were produced by integrating radiographs across a given duration of the experiment. Data analysis:

660

665

670

675

680

640

The collected radiographs underwent several processing steps to extract meaningful information. First, we applied a flat field correction to eliminate image artefacts, utilizing 'flat' images which recorded the background before laser scanning. Subsequently, image stitching was employed to reveal the distribution of pores along the entire single track. Time-integrated images were obtained by overlaying the particles in successive frames onto one plane (*19*). The time-integrated images were produced to show the tungsten particles trajectories, as shown in Fig. 3E and 3F. After time integration, the keyhole becomes obscure due to the nature of time integration. We then applied a brown mask to represent the average keyhole shape. Note that the keyholes in the original radiographs are clear even with W tracers (see Movies S3 and 4).

The velocity of the tungsten particles is quantified in a reference frame of the substrate. This is achieved by transferring the data from the stationary melt pool to the laser scanning melt pool using image stitching (Movies S2 and S3).

The oscillation of the keyhole serves as an indicator of keyhole instability, with both its frequency and amplitude providing valuable insights into the extent of the oscillations. To quantify keyhole oscillation, we flattened the time-series radiographs using a reslicing technique (i.e., transient cross section (tCS)), yielding a reconstructed tCS image that exhibits the keyhole width evolution over time. This approach has the advantage of flattening a large number of frames, enhancing the statistics compared to the image segmenting method where each segmented image has to be checked manually to achieve precise segmenting, which limits the number of frames that can be quantified. The reconstructed tCS image, on the other hand, provides insights that are challenging to extract from a conventional time-series image stack alone.

In the reconstructed tCS image, the height of the white peaks represents the keyhole width. A bright peak in the time-sliced image is classified as a keyhole oscillation event if its height

685

690

695

exceeds the average keyhole width. The amplitude of the oscillation is defined as the difference between the height of the bright peak and the average keyhole width. The average keyhole oscillation frequency was quantified by counting the number of bright peaks, which varied with keyhole oscillation amplitude, and dividing that by the duration of the experiment.

Using approximately 2200 frames, we can calculate the overall frequency of keyhole oscillations by counting the number of bright peaks, as shown in Fig. S7. By grouping these peaks based on their height, we can also determine the frequency of keyhole oscillations at different amplitudes. For example, Fig. S6 illustrates the time-slicing process for a single keyhole oscillation event. The bright peak in the reconstructed tCS image (Fig. S6C) represents this oscillation event. The amplitude of this event is calculated by subtracting the average keyhole width from the height of the peak (measured from the lowest to the highest point of the bright pixels). Since the value exceeds 60 µm, this keyhole oscillation event is categorized as a strong oscillation.

Supplementary Text

1. Plateau-Rayleigh instability:

Plateau-Rayleigh instability states that a vertically falling stream of liquid will break up into droplets if its length is π times greater than its diameter (52). For the Right-Left scan case, as the 700 keyhole bottom shrinks, the aspect ratio $L/D = 4.6 > \pi$, where L is the keyhole length and D is the keyhole width near the bottom. In this regime, where L/D exceeds π , the Plateau-Rayleigh instability is activated, and the surface tension rapidly drives the keyhole collapse with the assistance from the surrounding flow. This agrees with previous studies (51), which demonstrated that keyholes with large ratios of keyhole depth to the width are susceptible to 705 collapse. Additionally, we assume that the local melt flow, resulting from the keyhole bottom shrinkage, moves rapidly with a major component in the horizontal direction towards the interface at a speed close to the migration speed of the interface. This partially explains why the large keyhole expansion can promote keyhole collapse as the induced horizontal flow would contribute to the keyhole pinch off. However, much higher imaging speeds would be required to 710 provide direct evidence to support this hypothesis.

2. Origin of TEMHD-Seebeck effect:

The Seebeck effect is essentially the direct conversion of thermal differences into an electric voltage driving current. It is typically utilized in solid state devices for applications such as waste heat recovery or in radioisotope thermoelectric generators that power space craft in deep space.

The governing principles rely on two key conditions. The first is a difference in the so called Seebeck coefficient, S, which is analogous to electron affinity. When two materials with differing S are placed into electrical contact, one acts like a p-type semiconductor, while the other like an n-type semiconductor. Consequently, charge separation (electron-hole pairs) occurs at the interface of the two materials with electrons migrating to the n-type. However, under isothermal conditions, an electrostatic equilibrium will be formed, and no current will be generated. The second condition is a thermal gradient along the interface; in the hotter end electrons will be promoted to higher energy states and consequently migrate to the cooler end. In the case of a single material of constant S, an electrostatic equilibrium will again form. However, when both conditions are satisfied a thermoelectric current is formed, where separation occurs in the hot region, electrons and holes migrate along the negative thermal gradient and recombine in the cold region. From convention, the direction of TE currents (I) will follow the migration of holes and be opposite to the migration of electrons forming a closed circulation. Therefore, the relative

720

715

730 difference in S between the materials, known as the Seebeck Power, determines the direction of J. Finally, the electric field then serves to preserve continuity. This is the basis of a thermocouple and is governed by a modified version of Ohm's Law and continuity.

$$\boldsymbol{J} = \boldsymbol{\sigma}(\boldsymbol{E} - S \nabla T), \nabla \cdot \boldsymbol{J} = 0.$$

S is strongly linked to material properties and in the semiconductor field new materials are constantly being developed to increase the magnitude of *S*, reaching values in excess of 900 μ V/K (53). Metals are not generally known for their semiconductor like properties, where a large value of *S* is typically considered to be in the region of $1 - 10 \mu$ V/K, two orders of magnitude lower. However, metals are typically highly conducting and depending on processing conditions $|\nabla T|$ can be large (especially in AM) driving a significant current.

740 In the presence of a magnetic field a Thermoelectric Lorentz force is formed, $F_{TE} = J \times B$. Typically, this is of little interest in solid state devices, however, in the context of liquid metal processing and solidification, it drives a flow known as Thermoelectric Magnetohydrodynamics (TEMHD). The Thermoelectric (TE) force magnitude relative to other inherent forces determines the significance of this secondary flow. For example in directional solidification of freckle forming alloys it can be comparable to buoyancy changing the formation of channels (17); in free undercooled growth can significantly alter the tip velocity and radius (54) and, as suggested here, in additive manufacturing can compete with Marangoni flow modifying melt pool dynamics and ultimately keyhole stability.

There are additional considerations in liquid metal processing compared to traditional solid state thermoelectric devices as *S* is dependent on temperature, phase and composition, all of which can vary in space and time. Strong variations of temperature in the liquid can lead to the formation of eddy currents, which can lead to thermoelectrically induced self-stirring, as observed in liquid Lithium (*14*). This is a special case as there is no interface per se, while in solidification, for many materials *S* often exhibits a discontinuity at the phase change from solid to liquid and for alloys, solute partitioning at the interface provides conditions to further increase the Seebeck power. The discontinuity at the interface is typically a much larger contributor to the Seebeck power than the dependency of *S* on temperature.

The presence of a large thermal gradient during keyhole mode laser melting process induces large thermoelectric currents (TECs). When a magnetic field is applied, the interaction between the TECs and the magnetic field produces a TE force, driving a secondary TEMHD flow. This TEMHD flow alters the net flow vortex and impacts keyhole oscillation. A schematic of the TECs structure is shown in Fig. S3. A similar TECs structure has been previously predicted by Chen(55) and Kao(34) in the laser melting process of Al alloys using numerical modelling.

It is also important to understand the spatial distribution of TE currents in a melt pool. In LPBF, unlike in DED, the melt pool always remains in contact with solid material, except for the top surface. The size of the melt pool in LPBF is considerably smaller (ca. $1/10^{th}$) than that for DED, and the formation of a keyhole takes place under high area energy density conditions. As a result of these differences, the spatial distribution of TECs in LPBF differs substantially from that reported in DED(19) where one has gas at the side surfaces and TECs are believed to concentrate at the solid/liquid boundary as they cannot circulate through the air. In the LPBF melt pool, TECs are likely to traverse the entire melt pool, as predicted in (34), creating a more extensive flow pattern throughout the pool when a magnetic field is applied.

3. Comparison to computer simulations:

Marangoni flow is suggested to be the initiator of keyhole instability, and both simulations (20, 26) and observations (30, 31) find that for conditions similar to ours, bulk flow velocities are

775

760

765

770

on the order of 1 m/s. By balancing the Lorentz force with the Marangoni Stress over a characteristic length scale (100 µm), $\sigma S |\nabla T| |\mathbf{B}| = \frac{\partial \gamma}{\partial T} \frac{\nabla T}{L}$, we deduce that a magnetic field in the order of 0.1 T is sufficient for the TE force to be comparable to Marangoni stress. Therefore, with $|\mathbf{B}| = 0.5$ T, TEMHD velocities should be of a similar order of magnitude to Marangoni flow.

In the case of a transverse magnetic field, simulations by Kao et al. (35) showed that depending on the sign of the magnetic field the corresponding TE force is orientated either 'down and forwards' or 'up and backwards', significantly changing the melt pool dynamics. Similarly, simulations by Wang et al (36) during LPBF show the same behavior with TE forces behind the keyhole orientated 'up and backwards' from a positive transverse magnetic field. They did not report the forces from changing the sign of the magnetic field, but we can infer that the sign of the TE force would be swapped.

- In this work, the tracer particles show this same dependency with particles following the same trajectory (e.g. 'up and backwards') and reversing when changing the sign of **B**. This 'up' or 'downward' force also leads to a TEMHD contribution to convective heat transport, which changes the melt pool morphology, namely the depth. Both of these effects can be seen in Figs. 3E and 3F, where changing the scan direction has an equivalent effect to changing the sign of **B**. This dependency on the sign of **B** also strongly suggests that the electromagnetic damping force, that goes as B^2 , is small compared to the TE effect. Note the flow velocity (1-2 m/s) as quantified using tungsten tracer particles is expected to be slower than the true melt flow; this is because the particles are accelerated by the drag force exerted by the Al melt. These flow velocities match well with the simulations (1-4 m/s) detailed by Wang and Yan (*36*).
- From the changes in melt pool morphology and particle behavior, we are confident that 800 TEMHD has a significant effect and can be comparable in magnitude to Marangoni flow. Marangoni flow is believed to be the initiator of keyhole instability and coupled with the directional dependence of TEMHD this study aims to show how TEMHD can compete against Marangoni flow to mitigate the instability initiation.

805

780

785

4. Kelvin-Helmholtz instability:

The existence of two fast-flowing fluids (liquid metal and the vapour plume) along the melt surface forms a stratification layer at the gas-liquid interface. The differences between the velocities and densities of the fluids along the stratification layer can induce a perturbation along with the interface, this is known as the Kelvin-Helmholtz instability (KHI)(56). The vapour plume has upward velocity, and its magnitude (a few hundred meters per second (6, 23)) is much 810 larger than that of the melt pool flow along the keyhole wall (up to 5 m/s by collecting available data from the literature (20, 30, 31, 36)). The KHI can be activated once the following conditions are satisfied (57): 1) $V_g \neq V_l$; 2) $(V_g - V_l)^2 > \frac{g(\rho_l^2 - \rho_g^2)}{k\rho_g \rho_l}$, where V_g is the vapour plume velocity within the keyhole, V_l is liquid melt velocity around the keyhole, ρ_g and ρ_l are the densities of the vapour plume and liquid melt, respectively, and k is the inverse of the perturbation 815 wavelength. Since $|V_g| \gg |V_l|$, the left-hand component is primarily determined by V_g ; the variation of melt flow has no significant impact on the KHI when applying a magnetic field. Assuming the density of the vapour and liquid is fixed, then k is the key factor influencing KHI. In the 'zero magnetic field' case, the value of k averaged $\sim 15/\text{mm}$ (quantified from radiographs), hence the above two conditions are satisfied and therefore KHI is activated. When 820 applying a magnetic field, the keyhole is stabilized, with smoother keyhole wall, and as such the averaged k approaches zero, bringing the right-hand component to infinity; and therefore, KHI is

suppressed or no longer activated. To summarize, the flow behind the keyhole initiates a protrusion on the rear keyhole wall causing the keyhole to fluctuate and become more unstable, and thus allowing KHI to be activated. Applying a magnetic field alters the melt flow, enabling the stabilization of the keyhole walls to smoother geometries which resist the KHI.

5. Comparison of keyhole oscillation frequency between Al and Ti alloys:

The measured keyhole oscillation frequency of 6.1 kHz in Al in this study is much lower than the frequency of 16 kHz in Ti64, as reported in (25). During a cycle of keyhole oscillation 830 (cyclic keyhole opening and closing), Marangoni flow tends to open the keyhole while the surface tension tends to close the keyhole. As Marangoni flow transports hot liquid to the rear of the melt pool, the keyhole opening temperature and thermal gradient drops to minimum and the keyhole opening is maximized. We hypothesise that as the thermal conductivity of Al is 237 W/mK, 20 times higher than that of Ti of 11.4 W/m K, the build-up of the thermal gradient of the 835 Al melt pool is lower, thus Marangoni flow is weaker than Ti. As such, in Al the time taken to finish a cycle of keyhole opening/closing is much greater, hence we observed a lower measured keyhole oscillation frequency. In addition, the dynamic pressure acting upon the surface of the keyhole from Marangoni flow acts alongside the surface tension and against recoil pressure, causing more frequent instabilities. Bernoulli's equation for dynamic pressure is $p_{dyn} = \frac{1}{2}\rho u^2$, 840 and as Ti has a much higher density than Al, the dynamic pressure will be higher. However, a systematic synchrotron study and high-fidelity simulation are required to verify these hypotheses and quantify the impact of thermophysical properties on the keyhole oscillation frequency, which is outside the scope of the current study.

845

850

855

860

825

6. Forces estimation:

For the volume forces estimation, with the values of $\sigma = 4.0 \times 10^6$ S/m, $S = 3.0 \times 10^{-6}$ V/K, $|\nabla T| \sim 1.0 \times 10^7$ K/m, |B| = 0.5 T, the TECs $|J| = \sigma S |\nabla T| \sim 10^8$ A/m². The magnitude of the TE force can be described as $J \times B \sim |J| |B| \sim 10^7$ N/m³. By converting the Marangoni surface stress to volume force, we introduce a hydrodynamic length scale (*L*), taken as half the melt pool depth (~100 µm), thereby the Marangoni force $\frac{\partial \gamma}{\partial T} |\nabla T| / L \sim 10^7$ N/m³, taking $\frac{\partial \gamma}{\partial T}$ as 3.1×10^{-4} N/(m · K) (29, 30, 44).

Regarding the pressure estimation, for a stable keyhole (neglecting fluid flow forces) the surface tension should approximately balance the recoil pressure $p_{\gamma} = \frac{\gamma}{r} \sim p_r$. For a surface tension of 1 N/m and a radius of 25 microns $p_{\gamma} = 4 \times 10^4$ Pa.

Taking volumetric TE force with $\sigma = 4 \times 10^6$ S/m, $S = 3 \times 10^{-6}$ V/K, $|\nabla T| = \frac{10^7 \text{K}}{\text{m}}$, $|B| = 0.5 T, L = 100 \,\mu\text{m}$, and adding 10% TE force variation calculated from Wang and Yan's work(*36*):

 $|\mathbf{F}_{TE}| = \sigma S |\nabla T| |\mathbf{B}| L \pm 10\% \sigma S |\nabla T| |\mathbf{B}| L = (6.0 - 7.5) \times 10^3 \text{ Pa}$

L is the viscous boundary layer, which for this study would be the melt pool width (into the page). We can also get a similar answer from dynamic pressure assuming a velocity of around 2 m/s:

$$p_{dyn} = \frac{1}{2}\rho u^2 = \frac{2700}{2} \times 2^2 = 5.4 \times 10^3 \text{Pa}$$

As mentioned, Marangoni stress is similar to TE e.g. $\frac{\partial \gamma}{\partial T} |\nabla T| = 3.1 \times 10^3$ Pa and dynamic pressure follows the same argument. We can therefore estimate that TE and Marangoni forces are about 7-18 % of the surface tension and recoil pressure.

7. Dimensionless driving force comparison

In traditional MHD, Electromagnetic Damping (EMD) is typically the dominant braking force and studies have shown that EMD can lead to control of the melt pool and stabilization of keyholes(11, 43). The authors of these studies make no mention of TEMHD. However, in this study, the interaction with inherent TE currents is suggested as the dominant mechanism. The key differences between these studies are the material used (Seebeck power) and the melt pool scale. In our work, we primarily use an AlSi10 wt.% alloy, where the high Si content adds semiconductor like properties to the system. Conversely, Liu et. al (11) and Cao et. al(43), use commercial Al6082 and 2A12, which have 0.6 wt.% and < 0.5 wt.% Si respectively and so may not exhibit strong thermoelectric properties. In these previous studies(11, 43), the melt pool depth $L \sim 3$ mm is much larger than in our study where the melt pool depth L is ~200 µm.

The main driving and braking hydrodynamic forces can be approximated as

 $|\mathbf{F}_{Ma}| = \gamma' |\nabla \mathbf{T}|/L$ $|\mathbf{F}_{TE}| = \sigma S |\nabla T| |\mathbf{B}|$ $|\mathbf{F}_{\mu}| = |\mu \nabla^2 \mathbf{u}| = \mu u/L^2$ $|\mathbf{F}_{EMD}| = |\sigma \mathbf{u} \times \mathbf{B} \times \mathbf{B}| = \sigma u |\mathbf{B}|^2$

where F_{Ma} is the Marangoni stress, divided by length scale, *L*, to become a volumetric force, F_{TE} is the thermoelectric force, F_{μ} is the viscous force and F_{EMD} is the electromagnetic damping force. A key aspect of the electromagnetic forces is that F_{TE} is dependent on the sign of *B*, while F_{EMD} depends on the double cross product and thus does not depend on the sign of *B*, instead going as $|B|^2$ in the approximation. In our work, we tested this dependency on the sign of *B*, demonstrating that the behavior is due to TEMHD. Kern et. al (37) observed that reversing the magnetic field switched the damping of humping during laser welding on/off, whilst Ambrosy et. al(42) found that reversing the magnetic field increased the melt volume of fully penetrating welds. Both studies further support our hypothesis. However, Liu et al (11) and Cao et. al(43) did not explore the influence of changing the magnetic field sign on the thermoelectric effect.

By calculating the Hartmann number $Ha = (\frac{|F_{EMD}|}{|F_{\mu}|})^{1/2} = |B|L(\frac{\sigma}{\mu})^{1/2}$ (defined as the square root of the ratio of electromagnetic damping (EMD) to viscosity) and the ratio of TE/EMD $\frac{|F_{TE}|}{|F_{EMD}|} = \frac{S|\nabla T|}{u|B|}$ (if the TE/EMD ratio is much larger than 1, TE is the main damping force), we can determine the primary damping force and thus identify the main factor controlling the flow. We took 5 different studies, listed in Table S3, and calculated the Hartmann number, which is typically used to characterize a MHD system. In all studies (including ours) Ha > 1, implying that EMD dominates over viscosity. However, we argue that for a given sign of **B**, the TE force also acts against Marangoni flow. From our study, $\frac{|F_{TE}|}{|F_{EMD}|} = 30$ (Table S3), indicating that TE dominates over EMD in this case. Kern et al. and Ambrosy et al. attribute some of their findings to the TE effect and in their works $\frac{|F_{TE}|}{|F_{EMD}|} \sim 1$, making it viable. Liu et al (11) and Cao et al (43) only discuss the EMD mechanism, but in both their studies $\frac{|F_{TE}|}{|F_{EMD}|} \ll 1$, hence EMD dominated.

8. Viscosity of the mixed suspension:

905

880

885

Large amounts of W may affect the viscosity. In our study 0.2 vol.% W particles were used. The viscosity of the mixed suspension (melt AlSi10Mg + solid tungsten) was calculated by (58): $\mu_m = \mu_f (1 + 2.5 \emptyset + 10.05 \emptyset^2)$

910 Ø is the volume fraction of the tungsten particles, set to $\emptyset = 0.002$, as quantified from the radiographs. The mixture viscosity is calculated to be $\mu_m = 1.005\mu_f$, a 0.5% increase in viscosity, which is negligible.

915

Note, that we performed the experiment under similar conditions with and without W tracers. The discussion of the keyhole dynamics is based on the non-tungsten experiment while the flow information is extracted from the separate tungsten experiment.



Fig. S1. In situ synchrotron X-ray imaging setup for the laser melting process. (A) The LPBF rig at 32ID, APS. (B) A CAD model showing the motion stage holding the substrate, equipped with two ring magnets. (C) The setup inside the environmental chamber.



Fig. S2. Comparison of keyhole pore distribution along the entire track. (A) RL, (B) RL-B scans.



Fig. S3. Schematic of the TE effect. (**A**) Structure of the thermoelectric currents (TECs) in a melt pool and the solid part under the conditions of (**B**) right to left scan (RL-B) and (**C**) left to right scan (LR-B) in the presence of a magnetic field.



Fig. S4. Melt pool geometry of AlSi7Mg with the magnetic field, with the scanning direction from (A) right to left (RL-B) and (B) left to right (LR-B), with consistent process parameters (P=225 W, V=0.5 m/s) for both scans. (C) and (D) are the corresponding cross-sections of the tracks (A) and (B).



Fig. S5. Comparison of the trajectories of ten W particles in the melt pools under the conditions of: (A) RL-B and (B) LR-B scans.



Fig. S6. Schematic of the transient cross section (tCS) image reconstruction process. (A) Time-series radiographs. (**B**) The extracted one-pixel-wide strips from the radiographs in (A). (**C**) The 40 strips combined cross-section image, the white peak represents one cyclic keyhole oscillation event observed in (A). (**D**) A 2000 strips combined cross-section image containing the 40 strips in (**C**).



Fig. S7. Comparison of the reconstructed tCS images at the location of 2/3 of the average keyhole depth. (A) RL, (B) RL-B scans, the duration of the scanning is 15 ms.



Fig. S8. Comparison of keyhole oscillation frequency with and without magnetic field. 200 W laser power, 0.5 m/s scanning speed.



Fig. S9. Keyhole splitting process producing a pore under the LR-B condition.



Fig. S10. Melt pool geometry of AlSi7Mg alloy without magnetic field. The scanning direction from (A) right to left (RL) and (B) left to right (LR), with consistent process parameters (P=225 W, V=0.5 m/s) for both scans. (C) and (D) are the corresponding cross-sections of the tracks (A) and (B).



Fig. S11. Influence of silicon content on the TE effect. (A) and (B) show the radiographic melt 960 pool shape of Al6061 with opposite scanning directions in the presence of a magnetic field orientated into the page. (C) and (D) show the radiographic melt pool shape of AlSi7Mg with opposite scanning directions with the identical magnetic field setup. The process parameters are consistent for these four scans (P=225 W, V=0.5 m/s).

Chemical elements	A16061	AlSi7Mg	AlSi10Mg
Manganese (Mn)	0.0 - 0.15	0	0
Iron (Fe)	0.0 - 0.70	0	0
Magnesium (Mg)	0.80 - 1.20	1	1
Silicon (Si)	0.40 - 0.80	7	10
Copper (Cu)	0.15 - 0.40	0	0
Zinc (Zn)	0.0 - 0.25	0	0
Titanium (Ti)	0.0 - 0.15	0	0
Chromium (Cr)	0.04 - 0.35	0	0
Other (Each)	0.0 - 0.05	0	0
Others (Total)	0.0 - 0.15	0	0
Aluminum (Al)	Balance	Balance	Balance

Table S1 Nominal composition of the substrate material (wt.%)

Materials	Laser power	Scanning speed	Spot size	Powder layer	Magnetic field
AlSi10Mg	200 W	0.5 m/s	47 µm	No	No
AlSi10Mg	200 W	0.5 m/s	47 µm	/	Yes
AlSi7Mg	200 W	0.5 m/s	47 µm	/	No
AlSi7Mg	200 W	0.5 m/s	47 µm	/	Yes
AlSi10Mg	225 W	0.5 m/s	47 µm	/	No
AlSi10Mg	225 W	0.5 m/s	47 µm	/	Yes
AlSi7Mg	225 W	0.5 m/s	47 µm	/	No
AlSi7Mg	225 W	0.5 m/s	47 µm	/	Yes
			47 µm	Yes, mixed	
AlSi10Mg	225 W	0.5 m/s		with W	Yes
				tracers	
Al6061	200 W	0.5 m/s	47 µm	/	No
Al6061	200 W	0.5 m/s	47 µm	/	Yes
Al6061	225 W	0.5 m/s	47 µm	/	No
A16061	225 W	0.5 m/s	47 µm	/	Yes

Table S2 In situ experiment list

Table S3 Comparison of studies						
Variable	Unit	Our work	Kern et. al(<i>37</i>)	Ambrosy et. al(42)	Liu et. al(11)	Cao et. al(<i>43</i>)
σ	MS/m	4	0.77	4.04	4.04	13
S	$\mu V/K$	3	1	0.5	0.03	0.03
∇T	K/µm	10	0.77	1.45	1.16	10
μ	mPas	0.38	6	1.54	0.38	1.54
u	m/s	2	2	2	2	2
L	mm	0.1	1.5	1.6	2	1.5
В	Т	0.5	0.3	0.58	0.2	0.42
На	-	5.2	5.1	47.5	41.5	57.9
TE/EMD	-	30.0	1.28	0.63	0.09	0.36
Notes: ∇T was estimated from $(T_{vap} - T_{melt})/L$, and S was assumed to be 2 orders of						
magnitude smaller for low silicon Al alloys in Liu and Cao's works.						

Movie S1

Comparison of keyhole dynamics with and without magnetic field, with the scanning direction from right to left (RL-B and RL scans). The material is AlSi10Mg. The laser spot size is ~47 μ m, the laser power is 225 W, and the scanning speed is 0.5 m/s. The frame rate is 140 kHz, and the exposure time for each frame is 595 ns. The scale bar is shown in Movie S1.

Movie S2

Flow visualisation by tracing tungsten particles in the melt pool for the RL-B scan. The material is AlSi10Mg. The laser spot size is \sim 47 µm, the laser power is 225 W, and the scanning speed is 0.5 m/s. The frame rate is 140 kHz, and the exposure time for each frame is 595 ns. Tungsten particles were added as flow tracers. The scale bar is shown in Movie S2.

Movie S3

Flow visualisation by tracing tungsten particles in the melt pool for the LR-B scan. The material is AlSi10Mg. The laser spot size is ~47 μ m, the laser power is 225 W, and the scanning speed is 0.5 m/s. The frame rate is 140 kHz, and the exposure time for each frame is 595 ns. Tungsten particles were added as flow tracers. The scale bar is shown in Movie S3.

Movie S4

Comparison of keyhole dynamics for the two opposite scans in the presence of a magnetic field (LR-B and RL-B). The material is AlSi7Mg. The laser spot size is \sim 47 µm, the laser power is 225 W, and the scanning speed is 0.5 m/s. The frame rate is 140 kHz, and the exposure time for each frame is 595 ns. The scale bar is shown in Movie S4.

990

975

980