

Analysis of oscillation patterns and wire feeding directions in wire electron beam cladding of CuAl8 on AlSi10Mg by quantifying the macroscopic element distribution

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Title:

Analysis of oscillation patterns and wire feeding directions in wire electron beam cladding of CuAl8 on AlSi10Mg by quantifying the macroscopic element distribution

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Abstract:

Surface alloying of Al alloys with Cu-based additives requires a homogeneous distribution of the alloying elements. This study investigated how the oscillation pattern and the wire feeding direction govern the element distribution in wire electron beam cladding of CuAl8 onto AlSi10Mg. Three oscillation patterns (concentric circles, medusa- and fish-shape) were applied with front feeding and back feeding. The time-averaged intensity distributions of the patterns were calculated as a comparative tool. The spatial distribution of the intensity controlled the cladding width and the mixing. The medusa-shape pattern and the fish-shape pattern yielded the most homogeneous element distribution, whereas the uniform but low intensity of the concentric circles left a Cu-rich band above an Al- and Si-rich band. Back feeding resulted in numerous Cu-rich swirls and poorer mixing than front feeding. The claddings consisted of Al₃Cu₄ dendrites and an interdendritic region of Al₂Cu and Al₂Cu + α -Al eutectic. For homogeneously mixed claddings, the hardness was governed by the dilution. To quantify the macroscopic element distribution, the coefficient of variation was determined from median-filtered BSE images, EDS mappings and hardness mappings. The coefficients of variation derived from the three measurement methods exhibited good qualitative and quantitative agreement, providing a valid basis for the quantitative assessment of element distribution.

Keywords:

wire electron beam cladding; direct energy deposition; oscillation pattern; feeding direction; element distribution; alloying

1 Introduction

1.1 Surface alloying of aluminum alloys with Cu-based additives

Surface alloying can improve the wear and corrosion resistance of Al alloys and can be performed by remelting a pre-deposited additive or by cladding [1]. In cladding, substrate and additive (wire or powder) are melted in a single step by an arc, a laser beam (LB) or an electron beam (EB), which eliminates pre-deposition, is easy to automate and provides high productivity and low porosity. Cladding is generally associated with low dilution, whereas surface alloying by remelting results in strong dilution with the substrate [1–3]. In the context of surface alloying, the goal is a homogeneous distribution of the alloying elements without unmelted particles or concentration gradients [4,5].

Additives based on Al, Co, Cu, Fe, Mo, Ni and Ti have been clad onto Al alloys [1,4,6–8]. The main challenges arise from differences in metallurgical and physical properties, which cause porosity, cracks, inhomogeneities and/or surface deformation [1,6,9]. Cu-based additives are preferred owing to their good wear and corrosion resistance [1,9] and their metallurgical and thermophysical compatibility with Al, which enables formation of defect-free layers [6,10,11]. The Al–Cu system exhibits several intermetallic phases (Table 1), which govern the hardness of the alloyed layer.

Table 1 Chemical composition range and hardness of intermetallic phases in the Al–Cu system reported in literature

Phase	Nominal composition	Chemical composition range	Hardness	Hardness
		[Cu at.-%] [12,13]	HV0.01 [14,15]	HV0.001 [16]
θ	Al ₂ Cu	31.9–33.0	630	632 ± 13 %
η_2	AlCu	51.9–54.8	905	794 ± 13 %
ζ_1	Al ₃ Cu ₄	56.0–57.5	930	-
δ	Al ₂ Cu ₃	60.0–64.0	-	-
γ_1	Al ₄ Cu ₉	64.0–69.0	770	636 ± 7 %

1.2 Electron beam cladding and beam oscillation

Owing to its high absorption on Cu and the vacuum environment, the EB is particularly suited for processing Cu, e.g. in welding [17], powder bed fusion (PBF) [18] and directed energy deposition (DED) [19,20]. In addition, the EB can be deflected quickly and flexibly, which enables freely programmable oscillation patterns. Deflection techniques such as single-spot/multi-spot technologies (meander, line scan, field technique) or multi-process technologies (combined cleaning, alloying and smoothing) have already been applied in EB surface alloying of Al alloys [9,10,21].

Oscillation patterns applied in wire-based EB welding, cladding and DED range from circles and ellipses to concentric circles and more complex shapes such as the medusa-, fish- or infinity-shape [22–24]. Front feeding combined with a concentric circle pattern is the most common configuration [25–28]. Pattern and size strongly affect the bead geometry: the pattern width perpendicular to the wire feed largely determines the cladding width [26], and concentric circles yield a symmetrical, shallow

penetration, whereas circular or elliptical patterns larger than the wire diameter cause deep penetration because the EB interacts directly with the substrate [22]. Low oscillation frequencies cause intense mechanical stirring, while high frequencies promote a more stable, thermally driven melt pool flow; defocusing results in smoother, wider beads with shallower penetration [29]. Moreover, the intensity distribution of the pattern can be tailored to support the melting of the wire [23].

1.3 Element distribution in cladding

The distribution of alloying elements is primarily governed by the melt pool flow, which is dominated by Marangoni convection. Since the surface tension depends on temperature and composition, a positive gradient results in inward flow and deep, narrow beads, a negative gradient in outward flow and shallow, wide beads, and a surface tension maximum between center and edge in a dual flow [30,31]. Consequently, the energy distribution of the heat source affects the mixing. An increased intensity at the edge of the laser beam profile yielded a more homogeneous microstructure over the layer depth [32]. A negative gradient can lead to a fine microstructure in the top area of claddings, while a positive gradient results in a fine microstructure at the bottom [33].

In EB cladding of Co- and Ni-based flux-cored wires on Al alloys, an increasing additive fraction led to inhomogeneous mixing, and the locally harder areas were prone to cracking [6]. In multi-wire DED-EB of Cu and steel, the element distribution was heterogeneous macroscopically but uniform microscopically, which was attributed to macrosegregation, density differences, rapid solidification and Marangoni convection [34]. In contrast, an infinity-shape pattern yielded a homogeneous Ni distribution over the seam depth in EB welding of duplex steel with a Ni-based filler wire [24].

Cu-based wires have rarely been used for alloying Al [35–37]. Harada et al. [35] clad Al–Cu wires onto AlMg4.5Mn by double-pulsed gas metal arc welding and obtained defect-free layers with up to 280 HV1, the hardness decreasing with increasing dilution. In dual-wire plasma DED (AlSi5 + CuAl8), mixing was largely homogeneous, but Cu-rich areas resulting from insufficient mixing of the CuAl8 wire promoted the formation of θ -Al₂Cu [37]. In laser cladding of a Cu-based powder onto AlSi10Mg, the upper layer was homogeneous (361–388 HV0.1), whereas the wide transition zone was inhomogeneous (141–797 HV0.1) [4]. Concentration maxima near the fusion boundary were attributed to convective mass transport [5] and, in combination with the differing densities of the intermetallic phases, to Marangoni convection, which resulted in a layered phase structure [38].

Lateral wire feeding introduces a directional dependence on the orientation of wire feed and travel direction (front, back or side feeding) [25,39]. In wire-based DED-LB, front feeding is generally superior to back feeding, as it provides a more stable melt pool, effective melting, a smoother surface and a higher deposition rate [39,40]. However, back feeding cannot always be avoided, e.g. when contours are built with a fixed wire feeder [41]. Homogeneous mixing has been reported for front feeding [25,42]. Yet the effect of the feeding direction on the element distribution has hardly been studied.

The macroscopic element distribution is typically characterized by energy-dispersive X-ray spectroscopy (EDS) point, line or area measurements, EDS mappings or hardness mappings [43–45]. Mappings are usually assessed visually, and EDS line scans are mostly taken along the bead center only. Mixing

indices based on the standard deviation of concentration fields have been used for microfluidics [46] and for simulated melt tracks [47]. To the best of the authors' knowledge, no metric has been established for the objective evaluation of the macroscopic element distribution across entire experimental cladding cross-sections.

1.4 Research aim

Cu-based additives are promising for improving the surface properties of Al alloys, provided that the alloying elements are distributed homogeneously. Wire EB cladding or DED-EB offer high potential in this respect, because freely programmable oscillation patterns allow the energy distribution to be tailored. This potential has not yet been fully exploited [23]. Moreover, oscillation patterns could play a crucial role in influencing material properties due to the growing interest in graded or in situ alloyed components as well as multi-material components [48]. However, a systematic and quantitative understanding of how the oscillation pattern and the wire feeding direction together govern the element distribution is missing.

This study therefore investigated wire EB cladding of CuAl8 on AlSi10Mg with three oscillation patterns (concentric circles, medusa- and fish-shape), the latter two in two alignments relative to the feeding direction. Front feeding, as the preferred configuration, was the main focus. Back feeding was included as a contrasting case to assess whether the feeding direction or the oscillation pattern dominates the element distribution. The intensity distributions of the patterns were estimated by a time-averaged superposition of the beam profile, which serves as a comparative tool. The study related the process parameters to the element distribution, phase formation and hardness. For this purpose, a metric was developed to quantify the macroscopic element distribution to enable a reliable evaluation.

2 Experimental details

2.1 Materials

The cast Al alloy AlSi10Mg was used as the substrate, with dimensions of $100 \times 50 \times 20 \text{ mm}^3$. The filler material was a solid CuAl8 wire (Ing. Heinrich Fladenhofer, Spezialreparaturen und Schweißerei e.U., Austria) with a diameter of $1.2 \pm 0.015 \text{ mm}$. This alloy was chosen for its excellent wear and corrosion resistance, and it is used in brazing [49] and additive manufacturing [28,50]. The chemical composition of the materials is provided in Table 2. The initial hardness values of both substrate and wire were in the same range (cf. Table 2).

Table 2 Chemical composition of the substrate (AlSi10Mg) and wire material (CuAl8) measured by optical emission spectrometry (OES) and EDS.

Material	Al [wt.-%]	Cu [wt.-%]	Mg [wt.-%]	Si [wt.-%]	Hardness HV0.1
Substrate: AlSi10Mg (OES)	bal.	-	0.3 ± 0.01	9.4 ± 0.4	100 ± 4
Wire: CuAl8 (EDS)	8.4 ± 0.7	bal.	-	-	100 ± 6

2.2 Electron beam cladding – setup and parameters

A K26-15/80 universal electron beam machine (pro-beam systems GmbH, Germany) with an integrated wire feeder unit (Dinse GmbH, Germany) was used for the experiments. The experimental setup is shown in Fig. 1a. The wire was positioned in the initial center of the electron beam via electron optical monitoring (Fig. 1b). The process parameters are listed in Table 3. The varied parameters were the oscillation patterns and the feeding direction (front feeding and back feeding). According to Syed and Li [39], for back feeding, the wire should be positioned at the leading edge of the molten pool. Therefore, the beam was shifted by 1 mm towards the wire (only for back feeding).

The concentric circle (Fig. 1c), medusa-shape (Fig. 1d) and fish-shape patterns (Fig. 1e) are proprietary pro-beam patterns consisting of 1000 spots each. They were selected to cover a wide range of intensity distributions, from a uniform distribution to local maxima in the x or y direction (Section 3.1). To the authors' knowledge, the fish-shape pattern has not been applied in cladding before.

Since the medusa- and fish-shape patterns are asymmetric in the x direction, two alignments relative to the feeding direction were investigated (Fig. 1b): alignment 2 (A2) is alignment 1 (A1) mirrored about the y-axis. For better visualization, pictograms in the figures indicate the alignment of the pattern relative to the wire.

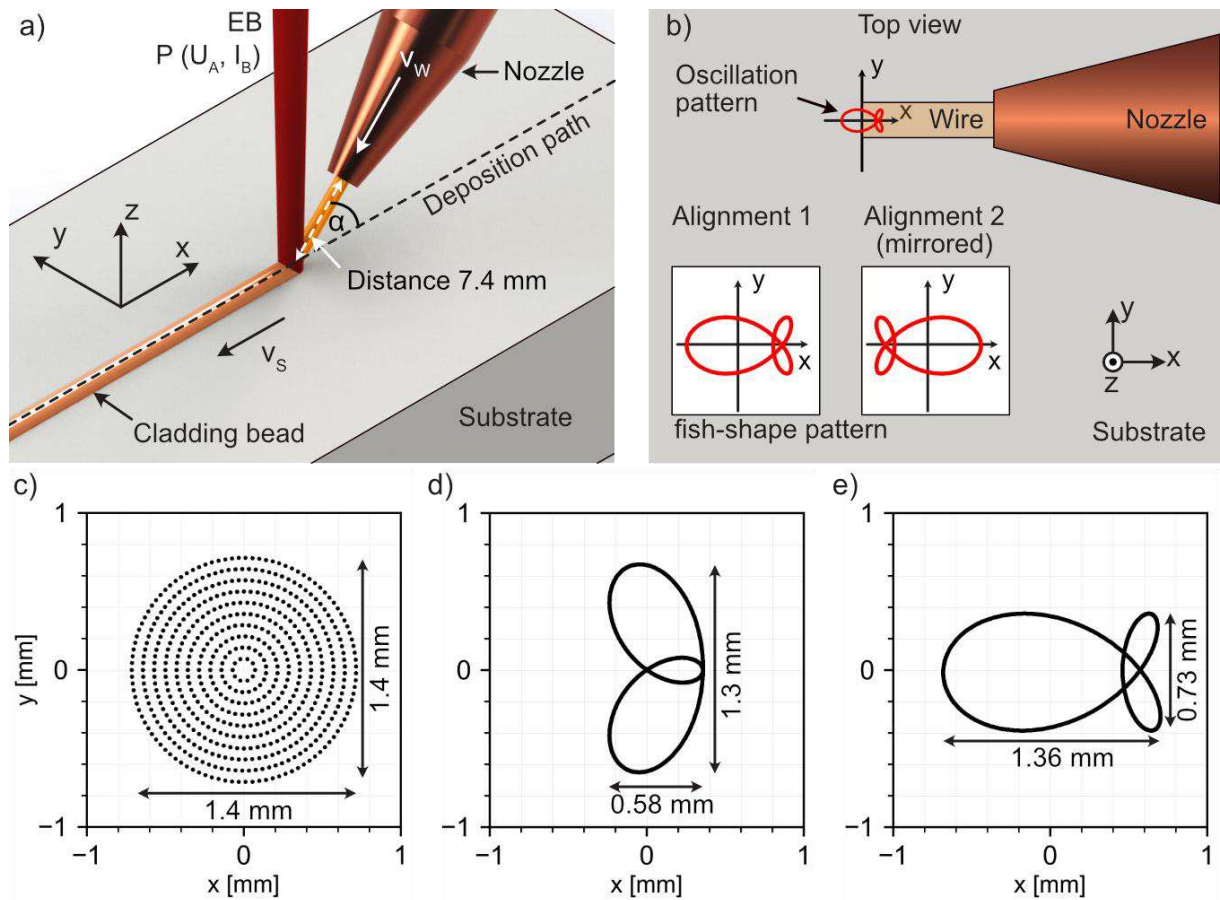


Fig. 1 Experimental setup of the electron beam cladding process: a) side view, b) top view with the fish-shape pattern in alignments 1 and 2; oscillation patterns used: c) concentric circle, d) medusa-

shape, e) fish-shape (alignment 1). Note: due to the small spot spacing, no discrete spots are visible in d) and e). Fig. 1b-d adapted from [51] with permission from ATZK and IFHTSE

Table 3 Process parameters for electron beam cladding

Parameter	Abbreviation	Unit	Values
Acceleration voltage	U_A	kV	60
Beam current	I_B	mA	14
Sample feed rate	v_S	mm/s	15
Wire feed rate	v_w	m/min	1
speed-factor (v_w / v_S)	k	-	1.11
Deposition rate	$\dot{m}$	kg/h	0.52
Feed angle	α	°	45
Frequency	f	Hz	3700
Focal point	f_p	-	substrate surface
Oscillation pattern	-	-	Concentric Circle / $A_x = 1.4$ mm; $A_y = 1.4$ mm Medusa-shape / $A_x = 0.58$ mm; $A_y = 1.30$ mm Fish-shape / $A_x = 1.36$ mm; $A_y = 0.73$ mm
Wire feeding direction	-	-	front feeding, back feeding

Two cladding beads were produced and analyzed for each combination of oscillation pattern and feeding direction. The bead geometry was measured on one cross-section per bead (Fig. 2). Since cladding is a DED process, the dilution D (proportion of substrate material in the bead) was calculated according to Eq. (1) [52].

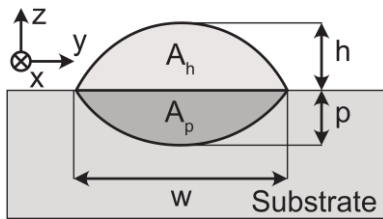


Fig. 2 Deposition geometry measurements; h ...bead height, w ...bead width, p ...penetration depth, A_h ...deposition area, A_p ...penetration area

$$D = \frac{A_p}{A_h + A_p} \cdot 100 \% \quad (1)$$

2.3 Calculation of the intensity distribution

The time-averaged intensity distribution, i.e. the beam power density averaged over one pattern period, was calculated for each oscillation pattern following Eq. (1) in Skryabinskyi et al. [53] and used to

compare the patterns. The calculation was implemented in Python; the script is available on OPARA (BeamPatternIntensity).

The static beam was assumed to have an ideal, rotationally symmetric Gaussian profile with the beam diameter d_{beam} defined at e^{-2} ($\approx 13.5\%$) of the peak intensity. Halbauer [54] determined $d_{beam} = 0.6$ mm for 600 W ($U_A = 60$ kV) at a distance of 770 mm on the same machine. The coordinates of the $N = 1000$ spots of each pattern were taken from the pattern files of the machine and scaled to the deflection field of 1.4 mm $\times$ 1.4 mm (cf. Table 3). According to [53], the relative intensity I at a point (x_i, y_i) is the sum of N point sources at the spots and N line sources along the jumps between consecutive spots, during which the beam remains switched on (Eq. (2)):

$$I(x_i, y_i) = \sum_{j=1}^N \exp\left(-\frac{r_{ij}^2}{2\left(\frac{d_{beam}}{4}\right)^2}\right) t_j + A(f) \sum_{j=1}^N \exp\left(-\frac{r_{i,j(j-1)}^2}{2\left(\frac{d_{beam}}{4}\right)^2}\right) t_{j(j-1)}, \quad (2)$$

where r_{ij} is the distance from (x_i, y_i) to spot j , $r_{i,j(j-1)}$ is the shortest distance from (x_i, y_i) to the jump from spot $j-1$ to spot j (including the return jump from the last to the first spot), and $A(f)$ is the ratio of the intensities of point and line sources, which depends on the pattern frequency f , and was set to 1 (constant beam power). Assuming that the scan generator realizes the same dwell time t_{spot} at all spots (Eq. (3)), the relative dwell time is $t_j = 1$ for every spot.

$$t_{spot} = \frac{1}{f \cdot N} \quad (3)$$

During a jump of length L_j from spot $j-1$ to spot j , the beam moves at the deflection speed v and requires the jump time $\tau_j = L_j/v$. Relative to t_{spot} , the relative jump time $t_{j(j-1)}$ follows from Eq. (4):

$$t_{j(j-1)} = \frac{\tau_j}{t_{spot}} = \frac{L_j \cdot f \cdot N}{v} \quad (4)$$

The deflection speed v was assumed to be constant at 4000 m/s, a value in the typical range of EB deflection systems [55]. At $f = 3700$ Hz, the jumps account for 0.4 % (medusa- and fish-shape patterns) and 4.1 % (concentric circles) of the pattern period. Since Eq. (2) assigns the full jump time to the entire jump path, long jumps are overweighted.

The calculation assumes (i) an equal dwell time at each spot, (ii) a constant deflection speed, neglecting acceleration of the deflection system, and (iii) no heat conduction, melt flow or interaction with the wire. The result thus represents the relative, time-averaged intensity on the substrate surface and serves to compare the patterns. Averaging over one pattern period was assumed appropriate, since the sample moves by only ≈ 4 μ m (v_s/f) per pattern cycle (≈ 0.27 ms), which is less than 1 % of d_{beam} , so that consecutive cycles overlap almost completely.

2.4 Characterization methods

2.4.1 Macroscopic and microscopic analysis

For the macroscopic analysis of the cladding beads, a Keyence VHX 600 light microscope was used. For each cladding bead, a cross-section was taken from the center of the cladding bead, perpendicular

to the sample feed direction. The cross-sections were ground and polished, with final polishing performed using an oxide polishing suspension (OP-S, Struers). No additional etching was carried out. The microstructure was characterized using scanning electron microscopy (SEM) (MIRA 3 XMU, TESCAN, Czech Republic) equipped with a backscattered electron detector and energy dispersive X-ray spectroscopy (Apollo XP, Ametek, USA).

To determine the area fractions of the phases in the microstructure, Fiji (version 1.54f) was used in combination with the Trainable Weka Segmentation plugin [56] (version 3.3.4). A classifier with three classes was trained to distinguish the dendrites (bright), Al_2Cu (dark gray) and the eutectic (black), the latter two forming the interdendritic region.

For characterization of the element distribution, overview images of the entire cladding beads were taken in backscattered electron (BSE) contrast ($3.18 \text{ mm} \times 2.39 \text{ mm}$, 1024×768 pixels, i.e. approx. $3 \mu\text{m}$ per pixel). Gain and brightness were kept constant and chosen such that only the cladding bead was visible, as the Al substrate has a significantly lower atomic number. The resulting grayscale image approximately represented the distribution of Cu and Cu-rich phases and was evaluated by its grayscale histogram. Al-rich phases at the fusion boundary and cracks had similarly low grayscale values (< 50) and could not be distinguished. Since BSE images provide limited information regarding absolute element content, energy-dispersive X-ray spectroscopy (EDS) element mappings were performed. To ensure comparability of these data, the same resolution as that used for the BSE images was applied.

For phase characterization, X-ray diffraction measurements (XRD, Bruker D8 ADVANCE diffractometer) were conducted with $\text{Cu-K}\alpha$ radiation covering the entire cladding bead and the substrate.

2.4.2 Hardness measurements

The hardness measurements were conducted with a fully automatic HP30S (Hegewald & Peschke MPT GmbH, Germany). Hardness mappings with HV0.1 and an x- and y-spacing of 0.1 mm were measured in both the cladding and the substrate material. Indentations within cracks were filtered out. For statistical calculations, the substrate material was filtered by excluding all hardness values below 100 HV0.1 from the calculation. In the cladding, no hardness values were below 100 HV0.1.

2.4.3 Quantitative determination of element distribution

A distinction was made between the microscopic (microstructural level) and the macroscopic (entire cladding bead) distribution of alloying elements. This work focuses on the latter. Here, mixing refers to the distribution of alloying elements within the cladding bead and should not be confused with dilution. The distribution of alloying elements was characterized using BSE images, EDS mappings and hardness mappings. In addition to the visual assessment, particularly of the BSE images and histograms, a common metric was applied to all three methods. EDS line profiles were not used, as they depend on the subjective choice of their position and do not represent the entire cladding bead.

The coefficient of variation (CV), also referred to as mixing index in the literature [46,47], was used as a comparative metric. This value is calculated according to Eq. (5) and is derived from the standard deviation σ relative to the mean μ . The CV allows the comparison of data variability even when the means differ. This is particularly important, as varying dilution levels resulted in different Cu contents

within the cladding beads. With respect to evaluation, a high *CV* indicates substantial relative variability, whereas a low *CV* suggests a homogeneous distribution of the data.

$$CV = \frac{\sigma}{\mu} \quad (5)$$

It is important to note that the BSE images and EDS mappings were acquired at a high resolution of 3 μm , thereby capturing information at the microstructural level. In contrast, hardness mappings average over a larger area. At a load of HV0.1, the indentation diagonal is approximately 43 μm for 100 HV0.1 and about 15 μm for 800 HV0.1. Additionally, a plastic zone surrounds each hardness indentation. For copper alloys, it is therefore recommended that the spacing between indentation centers should be at least three times the diagonal length to prevent interference [57]. Consequently, it was estimated that each hardness indentation effectively samples a square area with side lengths of up to 129 μm for 100 HV0.1 and 45 μm for 800 HV0.1.

For the analysis of the BSE and EDS data, the cladding beads were first manually cropped to ensure that only the cladding bead area (without contaminations) was analyzed. To establish comparability between the hardness mappings and the BSE and EDS analyses, a median filter combined with an increasing kernel was applied. A median filter was used because it works well with noisy images and preserves edges during filtering, which was useful for areas with large differences in element concentration. The median filter replaces the value of a pixel with the median of the values in its local neighborhood. The kernel defines the size of this neighborhood. Each kernel was applied to the original data. The kernel was continuously enlarged in order to obtain more macroscopic information, as an increasingly larger area was investigated. Given that each pixel corresponds to approximately 3 μm (lateral resolution of the BSE and EDS analyses), a direct correlation can be drawn to the sampled area. Thus, a kernel of 3 corresponds to an area of 3 pixels $\times$ 3 pixels or a lateral resolution of 9 $\mu\text{m} \times 9 \mu\text{m}$.

For the BSE images, the evaluation was based on grayscale values, while for the EDS mappings, the absolute Cu content of each pixel was used. To automate this process, a Python script was employed to calculate the *CV* for each kernel. In particular, but not only for pixels located at the edge of the cropped cladding bead, it was specified that the kernel would be valid if at least 50 % of the pixels within the kernel were situated inside the cladding bead. Cracks were not separately filtered out.

3 Results and discussion

3.1 Intensity distribution of the oscillation patterns

For the concentric circles (Fig. 3a), the even spot spacing resulted in a uniform intensity distribution with a maximum of 97 a.u., similar to the top-hat profiles typically used in laser cladding [32]. Owing to the lower spot density in the center, the intensity showed a dip there. The medusa-shape pattern (Fig. 3b) exhibited a concentrated distribution with a global maximum of 265 a.u. in the center, caused by the very high spot density, and two lateral local maxima (≈ 120 a.u.) shifted in the *y*-direction. Depending on the alignment, these lateral maxima may broaden the cladding bead. The fish-shape pattern (Fig. 3c) also showed a concentrated distribution. Its global maximum of 226 a.u. was located on the right side, where the spot density was highest, and was stretched in the *y*-direction; a local maximum

(≈ 83 a.u.) was located on the left side of the loop. The maxima were significantly farther apart than in the medusa-shape pattern. Due to the small amplitude in the y-direction ($A_y = 0.73$ mm), the positioning of the wire was particularly important for this pattern. For alignment 1, the intensity maximum of the medusa- and fish-shape patterns was located on the side where the wire was fed and melted.

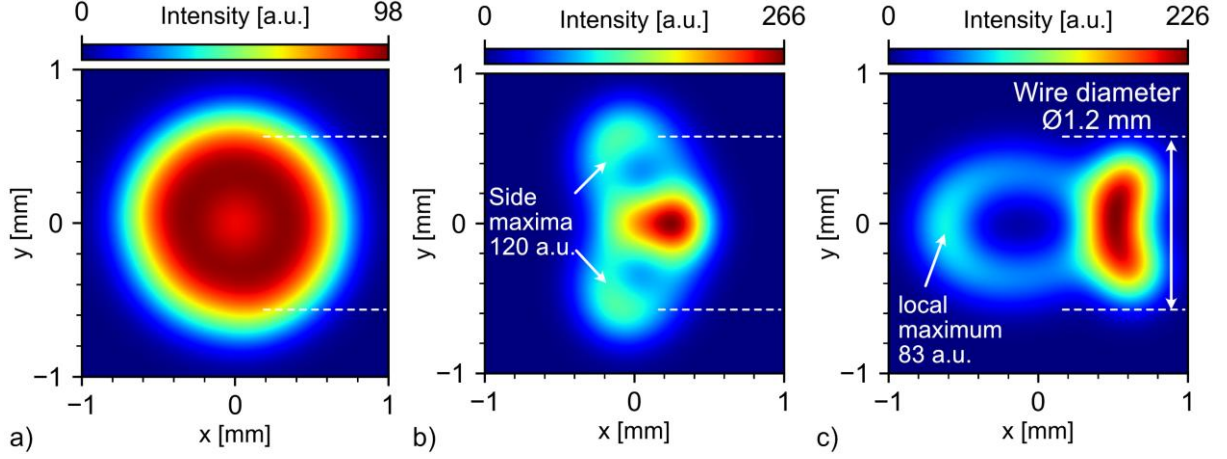


Fig. 3 Calculated time-averaged intensity distributions of the oscillation patterns (alignment 1, $f = 3700$ Hz): a) concentric circle, b) medusa-shape, c) fish-shape. Note the different intensity scales

3.2 Cladding geometry and dilution

The selected parameter set was suitable and reproducible for cladding, regardless of the oscillation pattern or its alignment (Fig. 4, top views), although the oscillation pattern amplitudes A_x/A_y were in some cases smaller than the wire diameter. Despite the high intensity maxima of the oscillation patterns, no keyhole formation was observed in the claddings (Fig. 4, cross-sections). Cracks were detectable in the overview or cross-sections of all samples.

With the exception of the cladding with concentric circles (Fig. 4e), which showed irregularities in cladding width, all other pattern variants produced uniform cladding beads with very fine, sometimes barely visible rippling. The medusa-shape pattern (alignment 2) had the highest width of 2.75 mm (Fig. 5a). The lateral maxima (Fig. 3b) extended beyond the side of the wire and led to direct melting of the substrate. This is also evident in the higher penetration depth at the edges of the cladding (Fig. 4b). This effect made the cladding bead wider and flatter. In contrast, this phenomenon was not observed with alignment 1. In this case, the wire melt continuously flowed into the melt pool and was kept liquid by the EB. As a result, the lateral intensity maxima had low direct interaction with the substrate and, therefore, minimal influence on the cladding width. This was also seen in the slightly flattened wetting angles at the edges of this cladding bead (Fig. 4a).

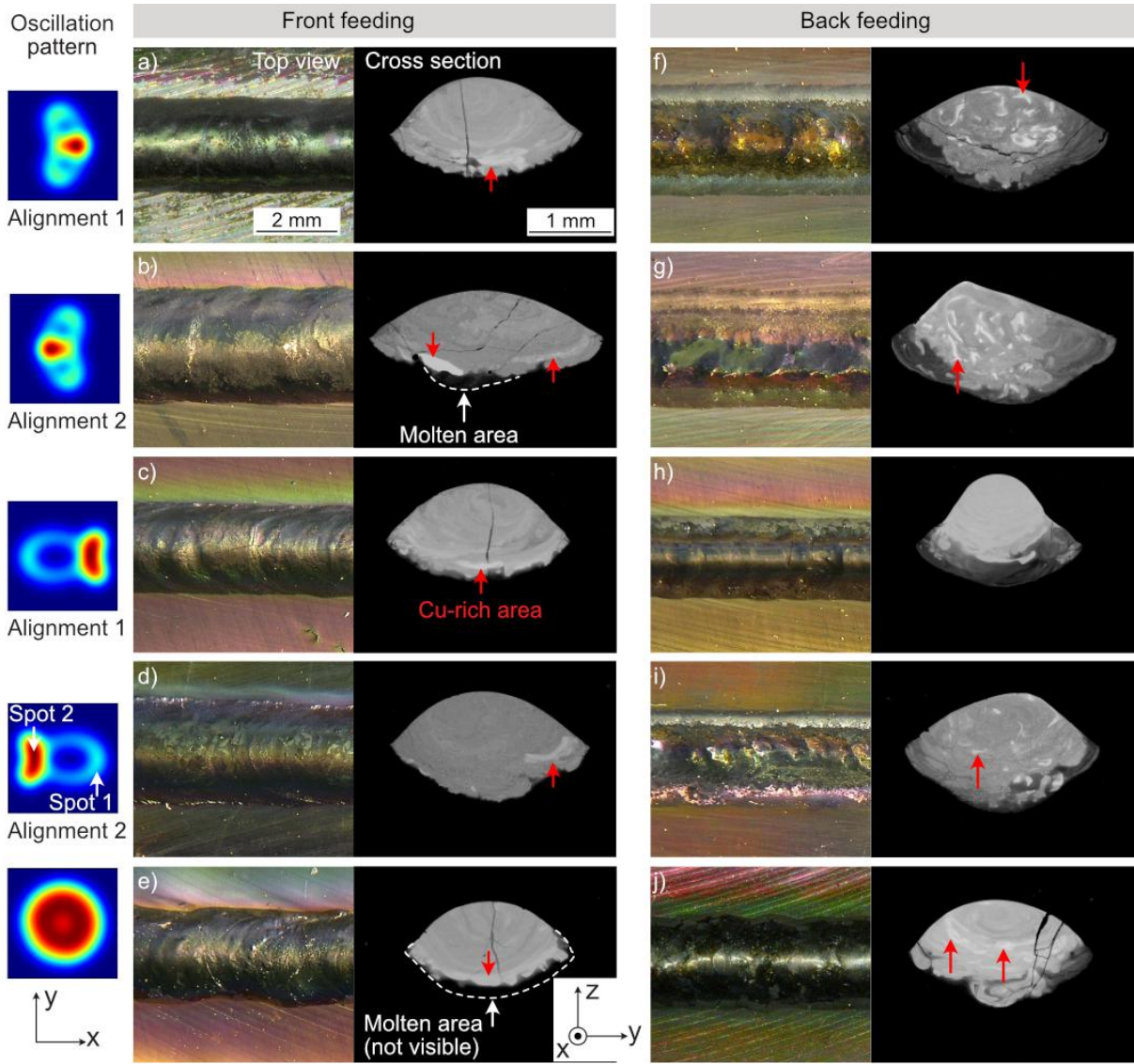


Fig. 4 Top views and cross-sections (BSE-Contrast) of the claddings depending on the oscillation patterns, alignment and feeding directions; (a-e) front feeding, (f-j) back feeding; Note: The brightness level of image (f) was adjusted to that of image (g). Fig. 4a, b, e, f, g and j adapted from [51] with permission from ATZK and IFHTSE

The smallest cladding width was observed with the concentric circles, although this oscillation pattern had the largest nominal width (Fig. 1c). The intensity at the edge of the oscillation pattern, combined with the applied power, was insufficient for melting. In contrast, the fish-shape oscillation pattern generated a larger width, even though its nominal pattern width was smaller than that of the concentric circles. Thus, the level and distribution of intensity play a decisive role in controlling the cladding width. The cladding heights of all beads were 0.6–0.7 mm (Fig. 5a).

The claddings with the concentric circles generated the lowest penetration depth (≈ 0.5 mm) due to the lowest intensity (Fig. 5b). Regardless of the oscillation pattern (medusa- and fish-shape), alignment 2 showed slightly higher penetration depths (0.6–0.7 mm) compared to alignment 1 (0.55 mm). A possible explanation is that with alignment 1 (intensity maximum on the wire side), a large amount of energy was used for melting the wire. In contrast, especially for the fish-shape pattern with alignment 2, a two-spot process had taken place. First, the local maximum on the right side (Fig. 4d, Spot 1) melted the wire.

Second, the intensity maximum on the left side (Fig. 4d, Spot 2) operated as a remelting process and led to deeper penetration. For the medusa-shape pattern, this effect was less pronounced due to the smaller amplitude in the x-direction.

The described phenomena for penetration depth also apply to the dilution. A linear correlation between penetration depth and dilution was observed (Fig. 5b). For the concentric circles the dilution was 43 %. The medusa- and fish-shape patterns achieved values of 44 % for alignment 1 and 51 % for alignment 2.

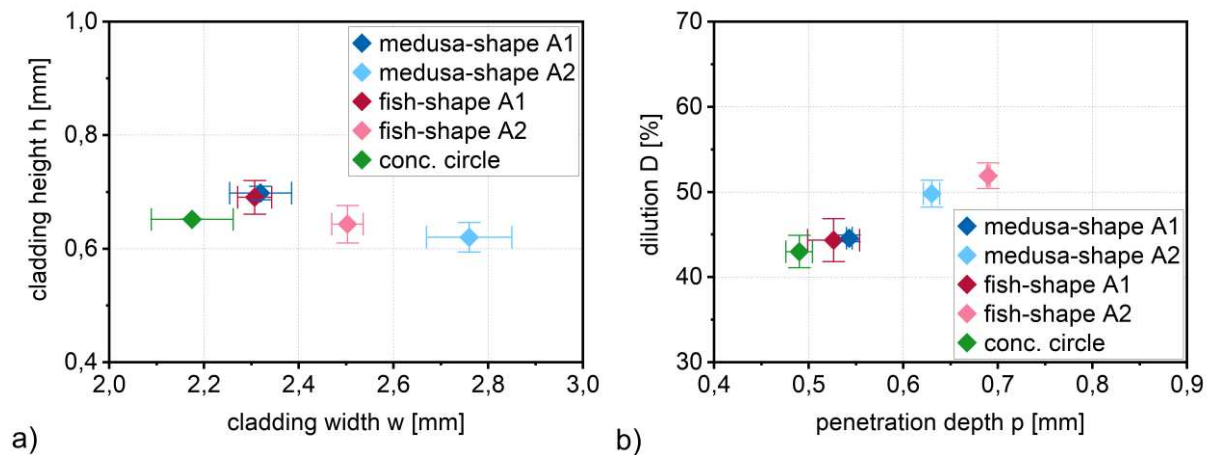


Fig. 5 Geometry of the claddings generated with front feeding; a) cladding height h vs. cladding width w and b) dilution D vs. penetration depth p ; A...Alignment

With back feeding, reproducible claddings without process interruptions or the lateral distortions typical for this feeding direction [39] were also obtained (Fig. 4f–j). Only the fish-shape pattern with alignment 1 led to partial droplet deposition (Fig. 4h). The intensity maximum on the wire side, combined with the shift of the pattern towards the wire in back feeding, melted the wire too far above the substrate. Since no droplet deposition occurred with front feeding for the same alignment, the shift of the pattern was considered to be the decisive factor. The unusual bead shape of the medusa-shape pattern with alignment 2 (Fig. 4g) cannot be explained yet.

Except for the fish-shape pattern A1 (droplet deposition), the cladding heights of 0.6–0.7 mm were comparable to front feeding (Fig. 6a). In back feeding, the EB first interacts directly with the substrate and forms a leading melt pool, into whose rear the wire melts. As a result, the medusa-shape pattern reached a large width of 2.72 mm independent of the alignment (Fig. 6a), unlike with front feeding. The penetration depths of 0.66–0.82 mm were 20–46 % higher than with front feeding (Fig. 6b, cf. Fig. 5b), confirming Müller et al. [25], and the dilution increased accordingly to 49–59 % (Fig. 6b).

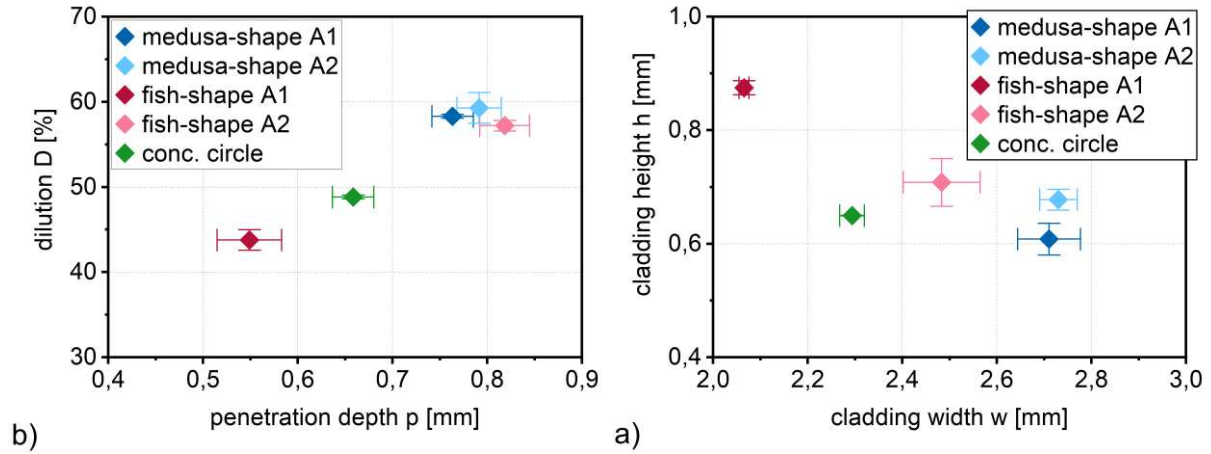


Fig. 6 Geometry of the claddings generated with back feeding; a) cladding height h vs. cladding width w and b) dilution D vs. penetration depth p ; A...Alignment

3.3 Qualitative analysis of the element distribution

The qualitative analysis of the elemental distribution was based on the BSE images (Fig. 4), the grayscale histograms of the BSE images (Fig. 7) and the EDS mappings (Fig. 8 and Fig. 9).

With front feeding, semicircular mixing was observed (Fig. 4a, c, and e). For the fish-shape pattern with alignment 2, no specific form was observed. Regardless of the alignment, isolated local accumulations were found in the lower or side areas for the medusa- and fish-shape patterns in the BSE images (Fig. 4a–d; red arrows) and the EDS mappings (Fig. 8a–d). As reported in the literature [38], the Cu enrichment at the bottom of the claddings was attributed to Marangoni convection and a high density of Cu-rich phases.

Based on visual evaluation, the fish-shape pattern with alignment 2 (Fig. 4d) achieved homogeneous mixing and revealed only one large copper-rich area on the right-hand side (Fig. 4d and Fig. 8d, red arrow). The reason was the special intensity distribution, which represents a two-spot process (Fig. 4d; Spot 1: Wire melting; Spot 2: Additional melting spot with a high intensity). After the wire had melted on the right side of the oscillation pattern (Spot 1), the EB maintained the melt pool with the intensity maximum (Spot 2), leading to better mixing and homogenization.

According to the grayscale histograms, the medusa-shape pattern with alignment 1 (Fig. 7a) as well as the fish-shape pattern with alignment 1 (Fig. 7c) and alignment 2 (Fig. 7d) had the most homogeneous mixing. All three histograms showed a narrow and high peak. These three samples were barely distinguishable through histograms. For the medusa-shape pattern with alignment 2, the main peak was flatter and broader, with an additional peak at a grayscale value of around 200 (Fig. 7b, black arrow), corresponding to a local accumulation of a Cu-rich phase (Fig. 4b).

In contrast, a continuous Cu-rich band above the fusion boundary was observed for the concentric circle pattern (Fig. 4e; red arrow). This band was detected in the histograms due to a pronounced secondary peak (Fig. 7e, black arrow). Below the Cu-rich band (Fig. 8e, red areas), there was an Al- and Si-rich band, which extended to the sides (Fig. 8e, areas marked with white dashed lines). In these regions, the substrate material had melted, leading to a nearly homogeneous distribution of Al and Si. Only in

the upper part of the Al-/Si-rich band a slight Cu gradient was detected, indicating that low mixing occurred in this area between the wire and the substrate material. No other parameter set showed such an even band across the cladding width in the lower part. A reason could be the low intensity and relatively uniform intensity distribution, in contrast to the other oscillation patterns with local maxima. This led to a less disturbed Marangoni convection. The result was a distinct layer structure: an Al- and Si-rich band formed from the melted substrate at the bottom, and a Cu-rich band from the wire melt lay on top with only a slight gradient between them, indicating that very little vertical mixing occurred. This demonstrates that a uniform top-hat-like energy input is insufficient to overcome density and surface tension effects to homogenize the melt pool.

The visual assessment of the BSE images corresponded well with the histogram analysis and EDS mappings. However, relying solely on histograms appears insufficient, as they primarily reveal only major heterogeneities. Specifically, smaller, brighter regions (e.g. Fig. 4a, red arrow) that are visually apparent in the BSE images are difficult or impossible to detect in the histograms.

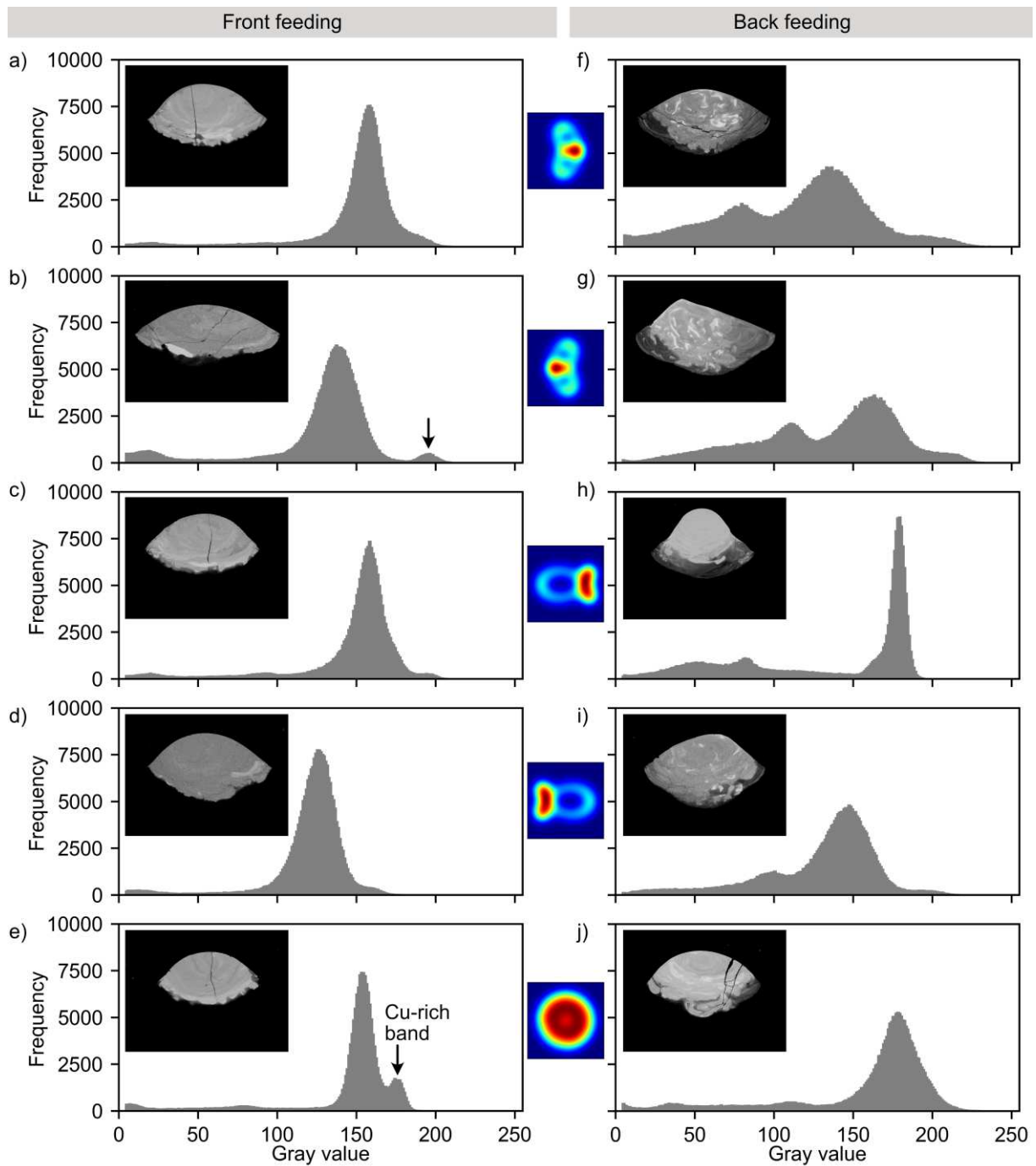


Fig. 7 Histograms of the grayscale distributions of the BSE images (see Fig. 4) of the claddings depending on the oscillation patterns, oscillation pattern alignments and feeding direction; a–e) front feeding, f–j) back feeding

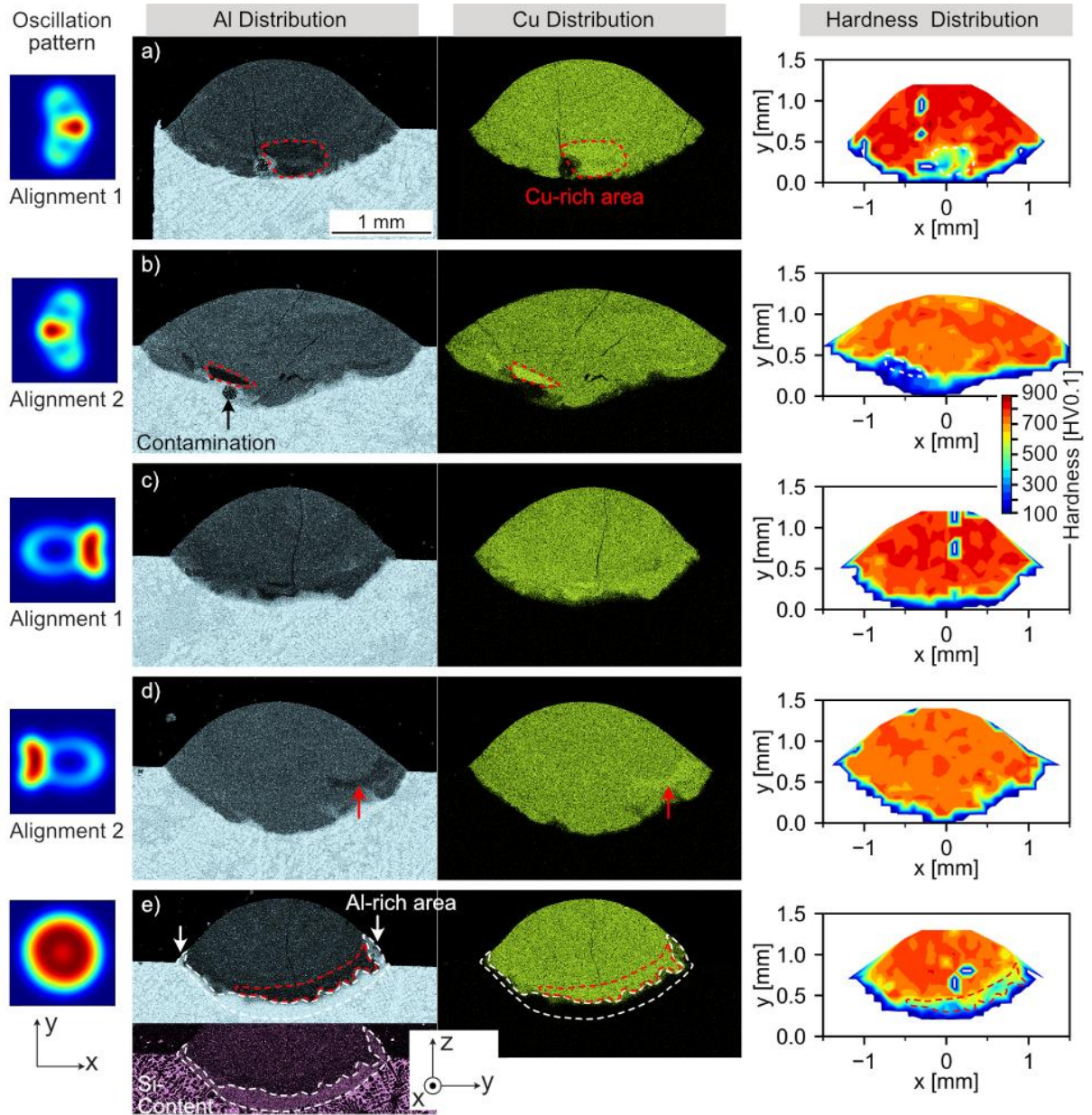


Fig. 8 Mappings of the Al and Cu distribution (EDS) and hardness of the claddings with front feeding depending on the oscillation patterns and the alignment; a), b) medusa-shape, c), d) fish-shape and e) concentric circle; The corresponding BSE images and histograms are given in Fig. 4a–e and Fig. 7a–e; Fig. 8a, b and e adapted from [51] with permission from ATZK and IFHTSE

With back feeding, many small Cu-rich areas (swirls) were visible in the middle and upper parts of the beads (Fig. 4f, g, i, j, red arrows), except for the bead with droplet deposition (Fig. 4h). Since the wire melts into the rear of the leading melt pool (Section 3.2) instead of passing through the entire pattern, the Cu melt enters the melt pool, which leads to incomplete mixing and numerous small swirls. Accordingly, the histograms showed several flatter and broader peaks and a higher baseline than with front feeding (Fig. 7f–j). The EDS mappings revealed a higher Al content at the bottom and lower sides of the beads (Fig. 9a–e, white arrows), particularly for the medusa-shape pattern with both alignments (Fig. 9a, b). The Cu-rich swirls (Fig. 9a, red arrows) are discussed in Section 3.4. The fish-shape pattern with alignment 1 consisted of an Al-rich bottom and a Cu-rich upper region due to droplet deposition (Fig. 9c). Unlike with front feeding, no continuous Al-/Si-rich band formed with the concentric circles (Fig.

9e). Overall, back feeding resulted in poorer mixing than front feeding, in agreement with Filippov et al. [42].

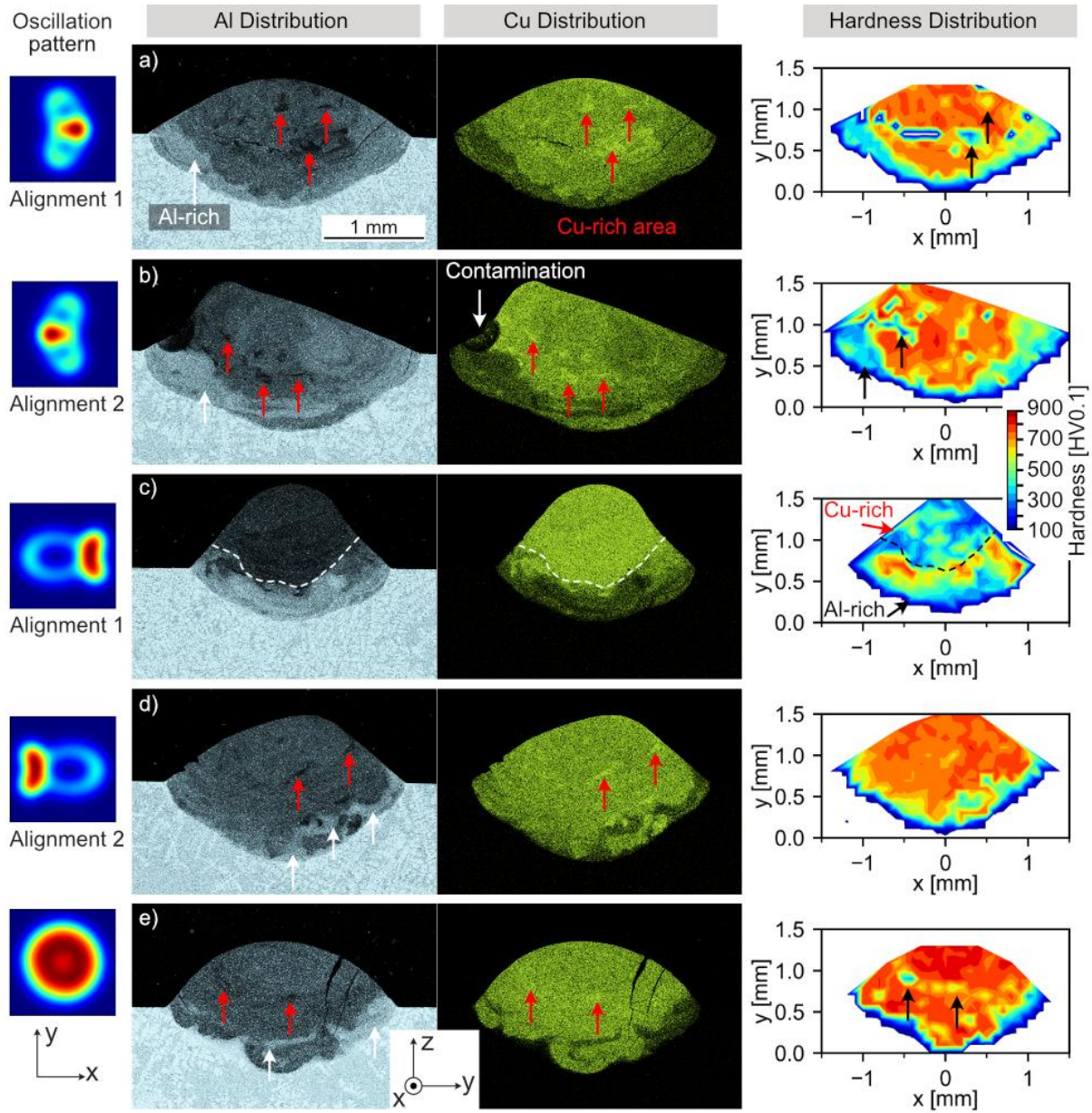


Fig. 9 Mappings of the Al and Cu distribution (EDS) and hardness of the claddings with back feeding depending on the oscillation patterns and the alignment; a), b) medusa-shape, c), d) fish-shape and e) concentric circle; The corresponding BSE images and histograms are given in Fig. 4f-j and Fig. 7f-j

3.4 Microstructure

The fish-shape pattern A2 (Fig. 10a) and the medusa-shape pattern A1 (Fig. 11a), which showed the most homogeneous mixing (Section 3.3), were selected for microstructure analysis. EDS point and area analyses (Table 4) were carried out in characteristic regions (marked in Fig. 10b, c and Fig. 11b). XRD identified the phases Al, Cu, Si, $\text{Al}_9\text{Cu}_{11.5}$ (also named $\zeta_2\text{-Al}_3\text{Cu}_{4.5}$ [58]), Al_2Cu and $\text{Al}_{3.25}\text{Cu}_{9.75}$ (also named $\gamma_1\text{-Al}_4\text{Cu}_9$ rt [59]) in both cladding beads.

In the middle section of the fish-shape A2 bead, three distinct regions were found (Fig. 10b). Dendrites made up 70 % of the area and contained 59 ± 1 at.-% Cu (Table 4, EDS1); together with the XRD

results, they were identified as Al_3Cu_4 . Between some dendrites, an additional, darker phase with a lower Cu content had formed (Fig. 10b, red arrows), possibly AlCu , which was not detected by XRD owing to its small fraction. The interdendritic region (IDR, 30 %) consisted mainly of Al_2Cu (dark gray; Table 4, EDS2) and a small proportion of $\text{Al}_2\text{Cu} + \alpha\text{-Al}$ eutectic (black). Another eutectic structure in the IDR (Fig. 10b, labeled eutectic) was not further analyzed.

At the bottom of the transition zone (Fig. 10c), a fine (EDS5) and a coarse eutectic (EDS6) were followed by an area of mainly Al_2Cu dendrites (EDS4) with $\alpha\text{-Al}$ in the IDR. Above this, the typical microstructure of Al_3Cu_4 dendrites (EDS3) with Al_2Cu and fine eutectic in the IDR formed; the slightly higher Al content of EDS3 compared with EDS1 reflects the higher Al content near the bottom. The Cu-rich area on the right side (Fig. 10d) contained 67 ± 2 at.-% Cu (EDS7) and was identified as Al_4Cu_9 based on the composition range (Table 1) and XRD.

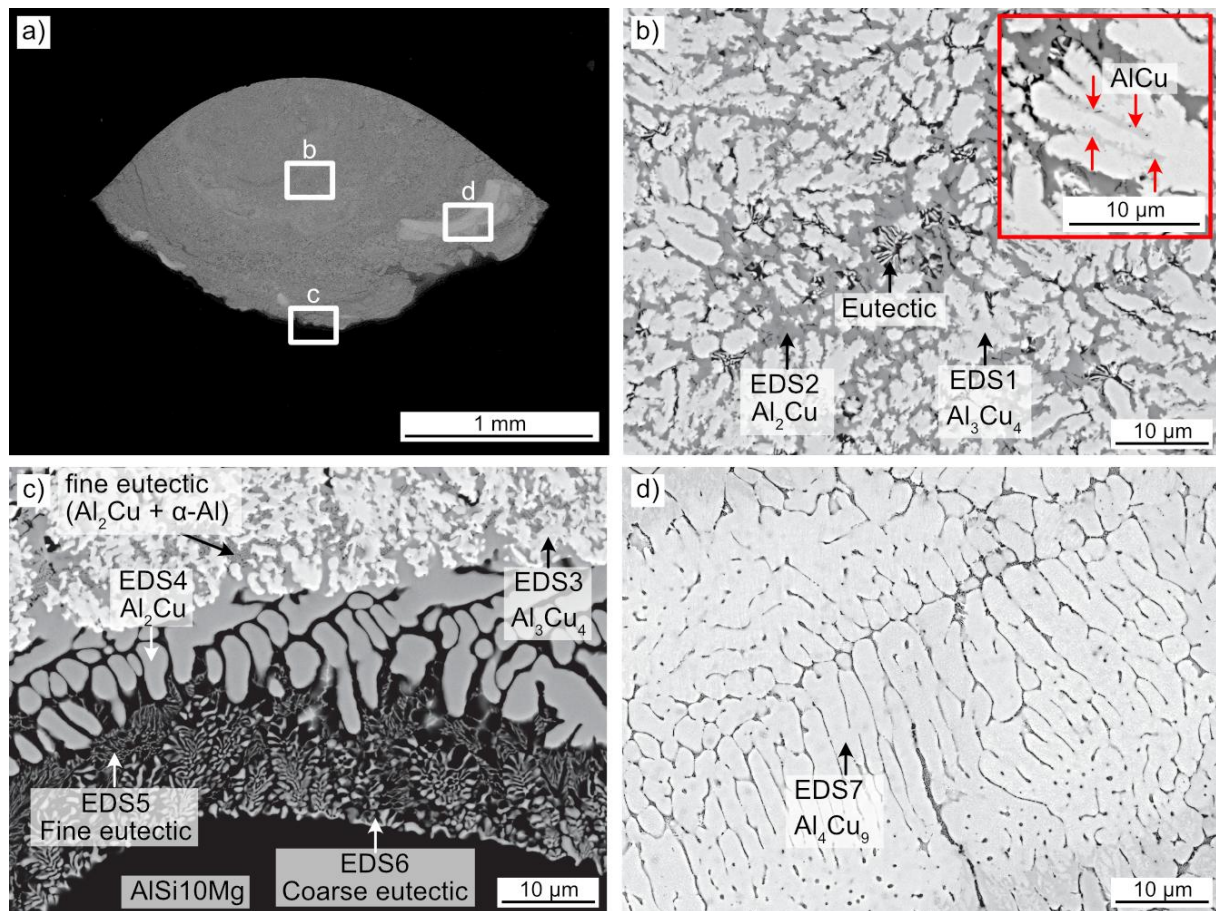


Fig. 10 Microstructure in BSE contrast of the cladding bead generated with the fish-shape pattern A2; a) overview, b) center area, c) bottom area, d) right side

The medusa-shape pattern A1 showed the same microstructure in the middle of the bead (Fig. 11b): Al_3Cu_4 dendrites with a composition matching that of the fish-shape pattern A2 (Table 4, EDS8 vs. EDS1) and $\text{Al}_2\text{Cu} + \alpha\text{-Al}$ eutectic in the IDR. However, the dendrites made up 89 % of the area (IDR: 11 %). This is attributed to the lower dilution ($D = 44$ % vs. $D = 51$ % for fish-shape A2) and thus higher Cu content, possibly enhanced by heterogeneous mixing.

In the bottom area (Fig. 11c), mixing was very heterogeneous, with a random distribution of Al- and Cu-rich areas instead of a gradient. Near the fusion boundary, the same phases (eutectic, Al_2Cu , Al_3Cu_4) formed as for the fish-shape pattern A2 (Fig. 10c), but the band of dendritic Al_2Cu differed in thickness. Partially Al-rich regions at the sides (Fig. 11d) contained Al_2Cu , fine eutectic and Al_3Cu_4 .

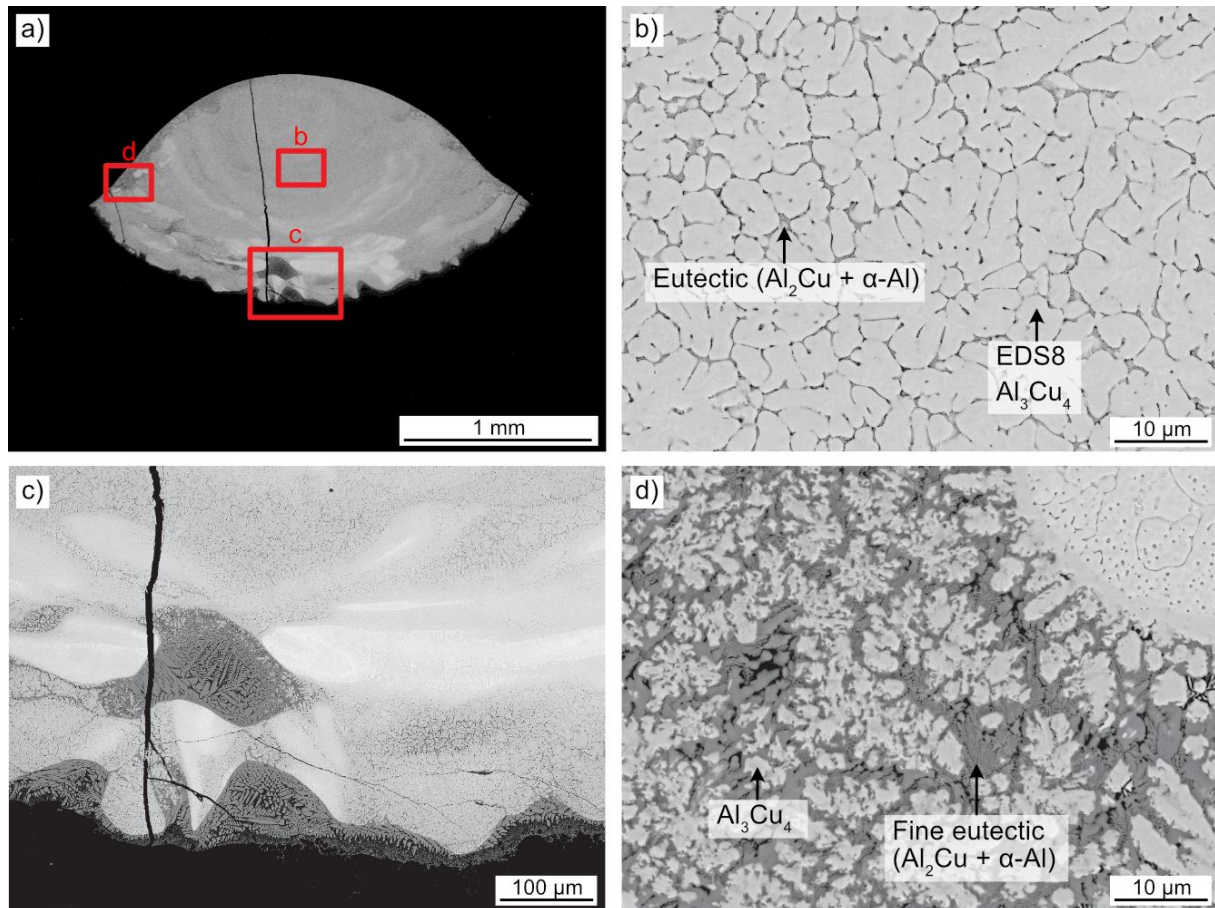


Fig. 11 Microstructure in BSE contrast of the cladding bead generated with the medusa-shape pattern A1; a) overview, b) center area, c) bottom area, d) left side

Table 4 Chemical compositions measured by EDS. The positions refer to the marked positions in Fig. 10, Fig. 11 and Fig. 12. Note: The data with the specified standard deviation were determined from at least five measurements. The marked phases * were identified with XRD.

position	Al [at.-%]	Cu [at.-%]	Si [at.-%]	Mg [at.-%]	possible phases
EDS1 (Fig. 10b)	41 ± 1	59 ± 1	-	-	Al ₃ Cu ₄ *
EDS2 (Fig. 10b)	60 ± 2	38 ± 2	3 ± 1	-	Al ₂ Cu*
EDS3 (Fig. 10c)	45 ± 2	55 ± 2	-	-	Al ₃ Cu ₄ *
EDS4 (Fig. 10c)	66 ± 1	34 ± 1	-	-	Al ₂ Cu*
EDS5 (Fig. 10c)	75 ± 1	9 ± 1	16 ± 1	1 ± 1	Eutectic (fine)
EDS6 (Fig. 10c)	84 ± 2	13 ± 3	3 ± 1	-	Eutectic (coarse)
EDS7 (Fig. 10d)	33 ± 2	67 ± 2	-	-	Al ₄ Cu ₉ *
EDS8 (Fig. 11b)	39 ± 1	61 ± 1	-	-	Al ₃ Cu ₄ *
EDS9 (Fig. 12b)	17	83	-	-	Cu
EDS10 (Fig. 12b)	31	69	-	-	Al ₄ Cu ₉
EDS11 (Fig. 12b)	38	62	-	-	Al ₃ Cu ₄
EDS12 (Fig. 12b)	60	37	3	-	Al ₂ Cu

The Cu-rich region at the bottom (Fig. 4b) and the swirls typical of back feeding (Fig. 4f) were examined in more detail. The Cu-rich regions consisted of Cu solid solution (Table 4, EDS9). Below such a region, i.e. on the Al-rich side (Fig. 12a), a very thin layer, probably Al₄Cu₉, was followed mainly by Al₂Cu with eutectic in the IDR, confirming that Cu-rich regions promote Al₂Cu [37]. Above this region, on the Cu-rich side (Fig. 12b), wider bands of Al₄Cu₉ (EDS10) and Al₃Cu₄ (EDS11) formed, followed by the typical microstructure of Al₃Cu₄ with Al₂Cu (EDS12) in the IDR (cf. Fig. 10b).

The swirls (Fig. 12c) showed the typical moon or elongated shape reported in [37,38]. They were not measured by EDS but are assumed to consist of Cu solid solution as well (cf. EDS9), whereas Wang et al. [38] identified such Cu-rich phases as Al₄Cu₉. Around the swirls, a similar band of Al₄Cu₉ and Al₃Cu₄ formed almost symmetrically (Fig. 12d), since the Cu content was similar on both sides. Thus, unlike in [37], the Cu-rich regions promoted the Cu-rich phases rather than Al₂Cu.

This difference is attributed to the significantly higher Cu content in the cladding beads. The observed phases resemble those in laser-welded Al–Cu overlap joints [13,43]. Dimatteo et al. [43] found Al₃Cu₄ and Al₄Cu₉ when the Cu content of the weld seam exceeded 50 at.-%. In contrast, no Al₃Cu₄ formed between Al₄Cu₉ and Al₂Cu in butt-welded Al–Cu joints [60].

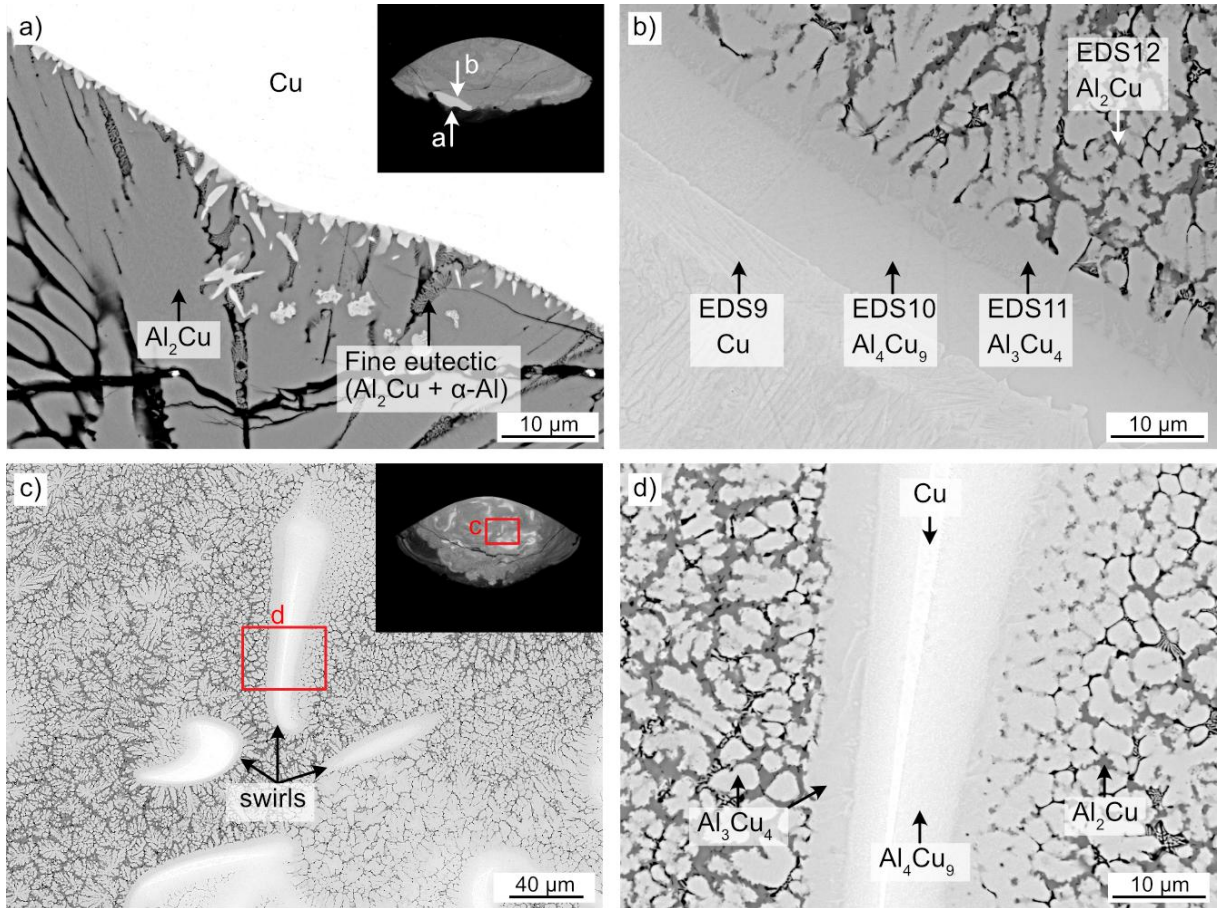


Fig. 12 Microstructure in BSE contrast of Cu-rich phases in the cladding beads; a) and b) medusa-shape pattern A2 (Fig. 4b, front feeding); c) and d) medusa-shape pattern A1 (Fig. 4f, back feeding). Note: Image b) was made with a lower gain setting

3.5 Hardness distribution

For front feeding, the median hardness ranged from 730 HV0.1 to 800 HV0.1 (Fig. 13; mappings in Fig. 8). For the medusa- and fish-shape patterns, the medians were nearly identical for the same alignment (≈ 800 HV0.1 for alignment 1, ≈ 730 HV0.1 for alignment 2). The lower hardness with alignment 2 results from its higher dilution (51 ± 2 % vs. 44 ± 2 %) and thus different phase fractions: the measured values are mixed values of the hard $\text{Al}_3\text{Cu}_4/\text{AlCu}$ dendrites and the softer, Al_2Cu -rich IDR (Table 1), and the dendrite fraction was 89 % for the medusa-shape pattern A1 but only 70 % for the fish-shape pattern A2 (Section 3.4). Consistently, the histogram peaks lay at higher grayscale values for alignment 1 (Fig. 7a, c) than for alignment 2 (Fig. 7b, d).

The concentric circle pattern had a similar dilution (43 ± 2 %) to alignment 1, but its poor mixing in the lower part caused a high scatter of the hardness values (Fig. 13).

As expected, the hardness scattered strongly for back feeding owing to the heterogeneous element distribution (Fig. 9, Fig. 13). For the medusa-shape pattern with both alignments, low hardness values occurred at the left and right edges with increased Al content (Fig. 9a, b, white arrows), where the lateral intensity maxima melted the substrate without achieving good mixing. In the center, the Cu solid solution swirls locally reduced the hardness (Fig. 9, red and black arrows).

The fish-shape pattern with alignment 1 showed three hardness zones (Fig. 9c): a Cu-rich upper region (300–600 HV0.1), a heterogeneously mixed middle region (up to 800 HV0.1) and a lower region with reduced hardness due to its low Cu content, consistent with the lower hardness of Cu- and Al-rich phases (Table 1).

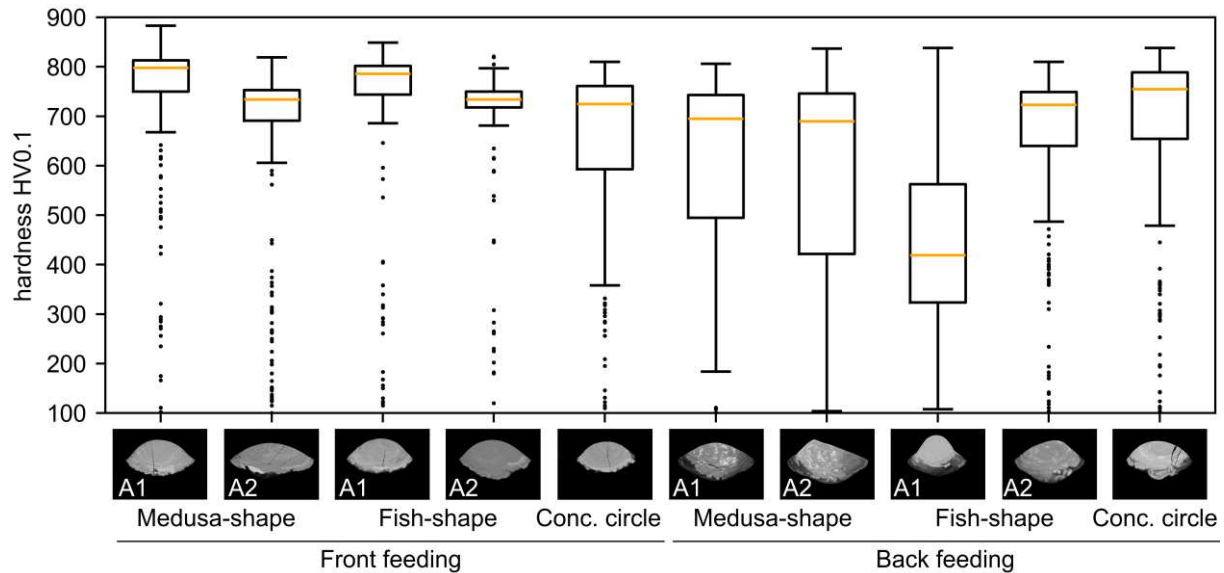


Fig. 13 Boxplot diagrams calculated from the hardness mappings depending on the oscillation patterns, alignments and the feeding direction; medians marked in orange

3.6 Quantitative analysis of the element distribution

For the quantitative analysis, all front-feeding claddings and, for comparison, the two back-feeding claddings with clearly visible inhomogeneities (medusa-shape A2, fish-shape A1) were evaluated. Fig. 14 shows the CV as a function of the kernel size for the BSE (a) and EDS data (b), with the equivalent lateral resolution on the secondary x-axis; the filtered images are given in the appendix as Fig. 16 and Fig. 17.

The CV decreased for both the BSE data (Fig. 14a) and the EDS data (Fig. 14b) with increasing kernel size. This was attributed to the high resolution of the SEM, as the original data – without kernel application – contained microstructural information. Notably, the CV for the EDS data (Fig. 14b) dropped much more sharply than that for the BSE data up to a kernel size of 5. Unlike the BSE images, the EDS mappings exhibited significant noise, likely due to the mapping size, measurement time, and counts per pixel. The median filter heavily reduced this noise up to a kernel of approximately 5 (Fig. 17), which explains the steep decline in the CV. Consequently, this reduction at small kernel sizes was not considered mainly an effect of microstructural smoothing. This interpretation was supported by the CV trends in the BSE data (Fig. 14a), where such a strong effect did not occur. In the BSE data only a very small drop of CV was evident from kernel 1 to 3, which could be regarded as microstructural smoothing.

Both diagrams (Fig. 14a, b) revealed the lowest CV for the patterns of fish-shape A2 (blue lines) and medusa-shape A1 (red lines). For both BSE and EDS data, these samples also displayed the greatest change in CV value with increasing kernel size. The fish-shape A2 pattern exhibited a slightly greater reduction in CV (Fig. 14a, black arrow) from kernel 1 to kernel 3 compared to the medusa-shape A1

pattern. This deviation was attributed to the fish-shape A2 pattern having a more heterogeneous microstructure (compare Fig. 11b with Fig. 10b). As the kernel size increased, the influence of the microstructure on CV decreased, thereby reflecting the macroscopic element distribution. Consequently, the CV for these two samples was particularly low at high kernel sizes. A low CV was thus interpreted as indicating a homogeneous element distribution. Due to the minimal deviation in CV, the two samples were barely distinguishable from each other.

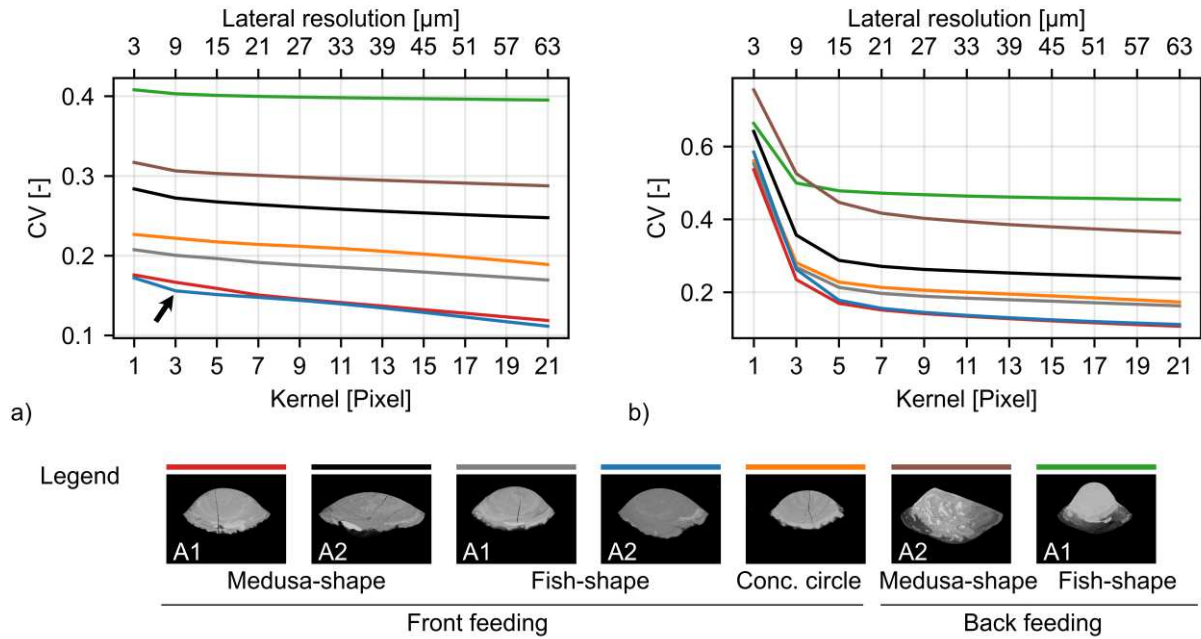


Fig. 14 Progression of the CV as a function of the kernel size used for the median filter for the BSE data (a) and the EDS data (b); Kernel 3 corresponds to an area of 3 pixels $\times$ 3 pixels. The lateral resolution was calculated based on pixel size (1 pixel corresponded to a resolution of 3 μm $\times$ 3 μm)

The highest CV values were determined for the two patterns produced using back feeding (Fig. 14, brown and green lines). The ranking of the CV values for BSE and EDS data agreed at high kernel sizes. For the BSE data, the kernel size did not alter the ranking of the CV. In the EDS data, however, the ranking of the top two lines (green, brown) changed from kernel 1 to kernel 7. The reason has not yet been conclusively determined. The cladding bead made with the fish-shape A1 pattern (back feeding) exhibited a strongly macroscopically separated element distribution, with one dark region (bottom) and one bright region (top). Kernels larger than 7 had little effect on the CV, as the macroscopic distribution was too large to be filtered.

For final validation, the CV from BSE, EDS, and hardness are presented in Fig. 15. To ensure comparability, the CV of the BSE and EDS data was determined using a kernel size of 15, which corresponds to a lateral resolution of 45 μm . This selection was based on the estimation of the sampled area in hardness measurements from Section 2.4.3, where the sampled area for 800 HV0.1 was approximately 45 μm . In Fig. 15, each bar is additionally labeled with a rank, indicating the relative position of the CV within a measurement method. The lowest CV was assigned rank 1 (most homogeneous distribution), and the highest CV was assigned rank 7 (most inhomogeneous distribution).

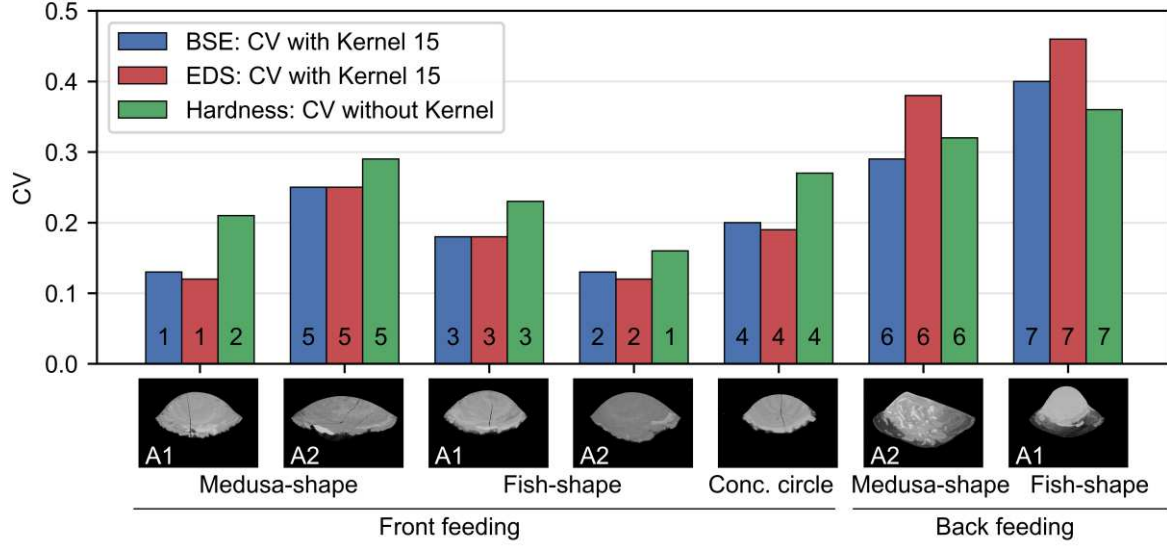


Fig. 15 Diagram of the CV values from the three measurement methods (BSE, EDS, and hardness) including a ranking (lowest CV corresponding to rank 1 and most homogeneous element distribution)

The comparison in Fig. 15 demonstrated good qualitative and, in particular, quantitative agreement of the CV across all three measurement methods for each oscillation pattern. This confirmed the assumption that the estimated lateral resolution of the hardness measurement correlated very well with the lateral resolution of the BSE and EDS data. The only exception was the medusa-shape A1 pattern (front feeding), where the CV derived from hardness (CV = 0.21) deviated from those of the BSE (CV = 0.13) and EDS data (CV = 0.12).

Of all conditions, the medusa-shape A1 pattern (CV range: 0.12–0.21) and fish-shape A2 pattern (CV range: 0.12–0.16) – both produced using front feeding – consistently exhibited the lowest CV and, accordingly, the best rank. These were also the two samples that were assigned a homogeneous element distribution based on visual observation. Differentiating between these two samples was not possible due to the small differences of the CV. One might consider assigning greater significance to the hardness measurements, as these data also involve information in the depth direction. However, distinguishing these two samples (rank 1 and 2) from the medusa-shape A2, fish-shape A1, and concentric circle patterns (all front feeding) was clearly achievable using the CV (ranks 3 to 5). The highest CV values were observed for the medusa-shape A2 pattern (CV range: 0.29–0.38) and fish-shape A1 pattern (CV range: 0.36–0.46) – both produced using back feeding – which also visually displayed the most inhomogeneous macroscopic element distribution.

The results show a direct correlation between the intensity distribution of the oscillation pattern and the final element homogeneity. The fish-shape A2 pattern, which was identified in Section 3.2 as having a two-spot intensity profile that acts as a remelting process, produced one of the lowest CV values. In contrast, the concentric circle pattern, with its uniform but low-intensity profile, led to poor mixing in the lower part of the cladding and a correspondingly higher CV (ranks 3–5). This demonstrates that not the peak intensity alone, but its spatial distribution, is the controlling factor for achieving a homogeneous element distribution.

The calculation of the CV using a median filter in combination with a kernel size of 15 proved to be a reliable metric for the quantitative determination of macroscopic element distribution in BSE and EDS data. Based on the CV, it was possible to distinguish between element distributions (rank 1–2 vs. rank 3–5), which were difficult to differentiate by subjective visual inspection alone.

4 Conclusions

This study investigated the influence of oscillation patterns in wire electron beam cladding of CuAl8 onto AlSi10Mg on the element distribution, microstructure and hardness. The following conclusions can be drawn:

1. Applying the time-averaged intensity calculation proved to be a fast tool for comparing oscillation patterns before cladding. The intensity distribution and the alignment of the pattern controlled the cladding geometry, particularly the cladding width. The spatial distribution of the intensity determined the homogeneity of the element distribution.
2. Front feeding resulted in better mixing than back feeding. The medusa-shape pattern A1 and the fish-shape pattern A2 achieved the most homogeneous element distribution, whereas the concentric circle pattern produced a Cu-rich band above an Al- and Si-rich band at the bottom of the bead. With back feeding, Cu-rich swirls occurred mainly in the middle and upper parts of the beads, whereas with front feeding and in the literature, Cu-rich regions are typically found at the bottom.
3. The middle area of the claddings consisted of Al_3Cu_4 dendrites, presumably with small fractions of AlCu , and an IDR of mainly Al_2Cu and $\text{Al}_2\text{Cu} + \alpha\text{-Al}$ eutectic. A higher Cu content, i.e. a lower dilution, increased the dendrite fraction. Regions of Cu solid solution were surrounded by bands of Al_4Cu_9 and Al_3Cu_4 on the Cu-rich side, whereas mainly Al_2Cu formed on the Al-rich side.
4. A direct process–microstructure–property relationship was demonstrated. For homogeneously mixed claddings (front feeding), the hardness was governed by the dilution rather than by the oscillation pattern, since the dilution controlled the fractions of the hard dendrites and the softer IDR.
5. The use of a median filter combined with a sufficiently large defined kernel (kernel 15 in this study) enabled the determination of CV values that described and quantified the macroscopic element distribution. A good qualitative and quantitative agreement of the CV was observed across the measurement methods (BSE, EDS, hardness), with the hardness-based CV of the medusa-shape pattern A1 as the only notable deviation. This also confirmed the conclusions drawn from visual assessment (primarily of BSE images) regarding element distribution. The agreement between microscopic measurement data (BSE, EDS) and mechanical testing data (hardness) was considered a strong validation of the evaluation routine.

The results demonstrate the potential of tailored oscillation patterns for EB cladding and additive manufacturing. Future patterns should build on the medusa-shape (alignment 1) and fish-shape (alignment 2) patterns. For multi-layer deposition, a multi-spot process such as the fish-shape pattern is recommended, in which the first spot melts the wire and the second spot remelts and mixes the melt pool. For multi-bead deposition with lateral overlap, the lateral intensity maxima of the medusa-shape

pattern are expected to promote mixing between adjacent beads. Future work will focus on controlling the dilution by parameter adjustment and/or preheating to prevent cracking.

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Richard Müller: Conceptualization, Methodology, Investigation, Visualization, Data Curation, Writing - Reviewing and Editing

Dominic Seidel: Investigation, Writing - Reviewing and Editing

Horst Biermann: Conceptualization, Supervision, Funding acquisition, Writing - Reviewing and Editing

Anja Buchwalder: Conceptualization, Supervision, Funding acquisition, Writing - Reviewing and Editing

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Volker, Weihnacht: Supervision, Funding acquisition, Writing - Reviewing and Editing

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the authors used Mistral AI and Claude (Anthropic) for language editing and programming. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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Appendix

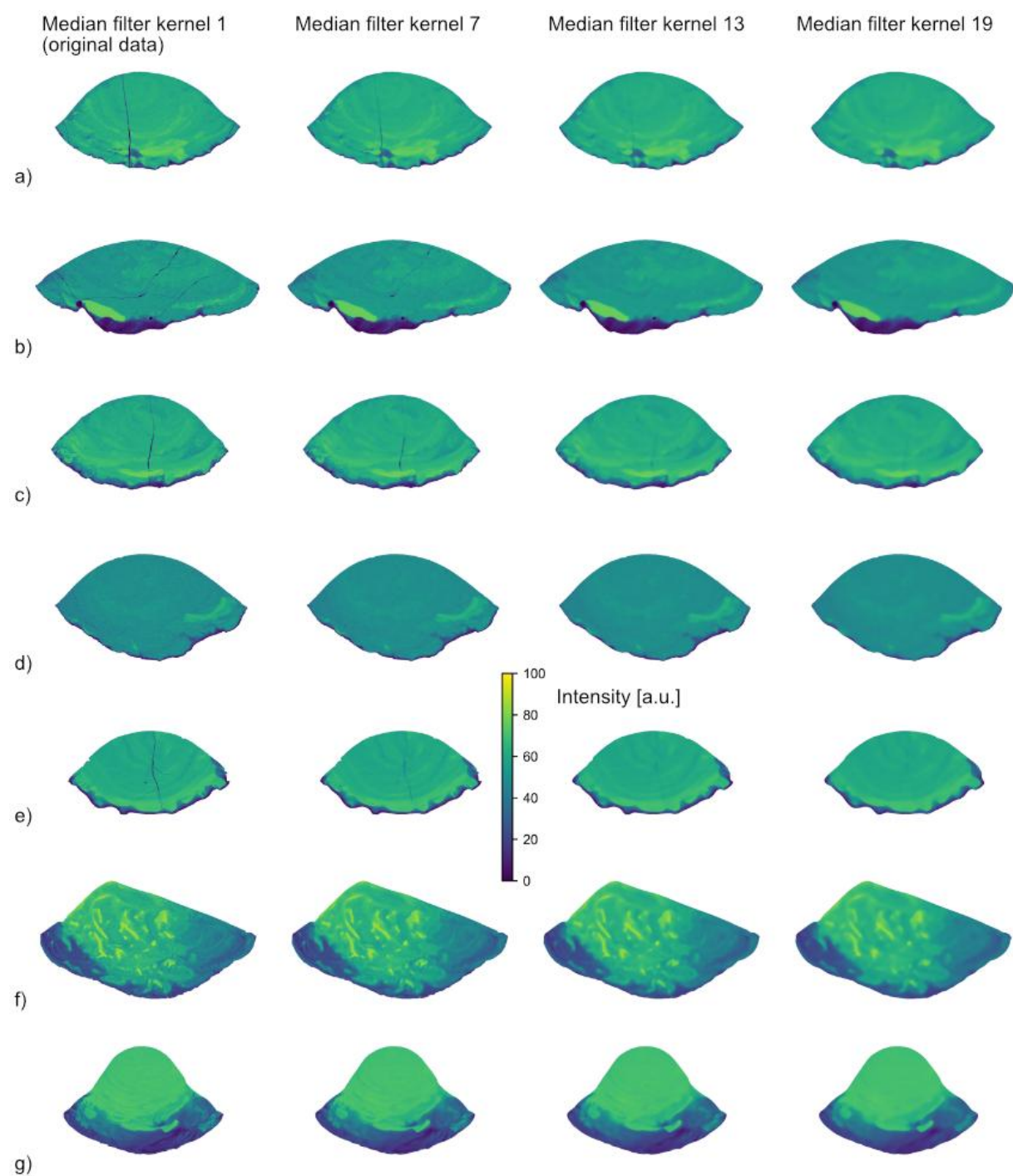


Fig. 16 Images of the BSE data filtered using the median filter and the applied kernel; a) Medusa-shape A1, b) Medusa-shape A2, c) Fish-shape A1, d) Fish-shape A2, e) Concentric circle (a–e front feeding), f) Medusa-shape A2 and g) Fish-shape A1 (back feeding)

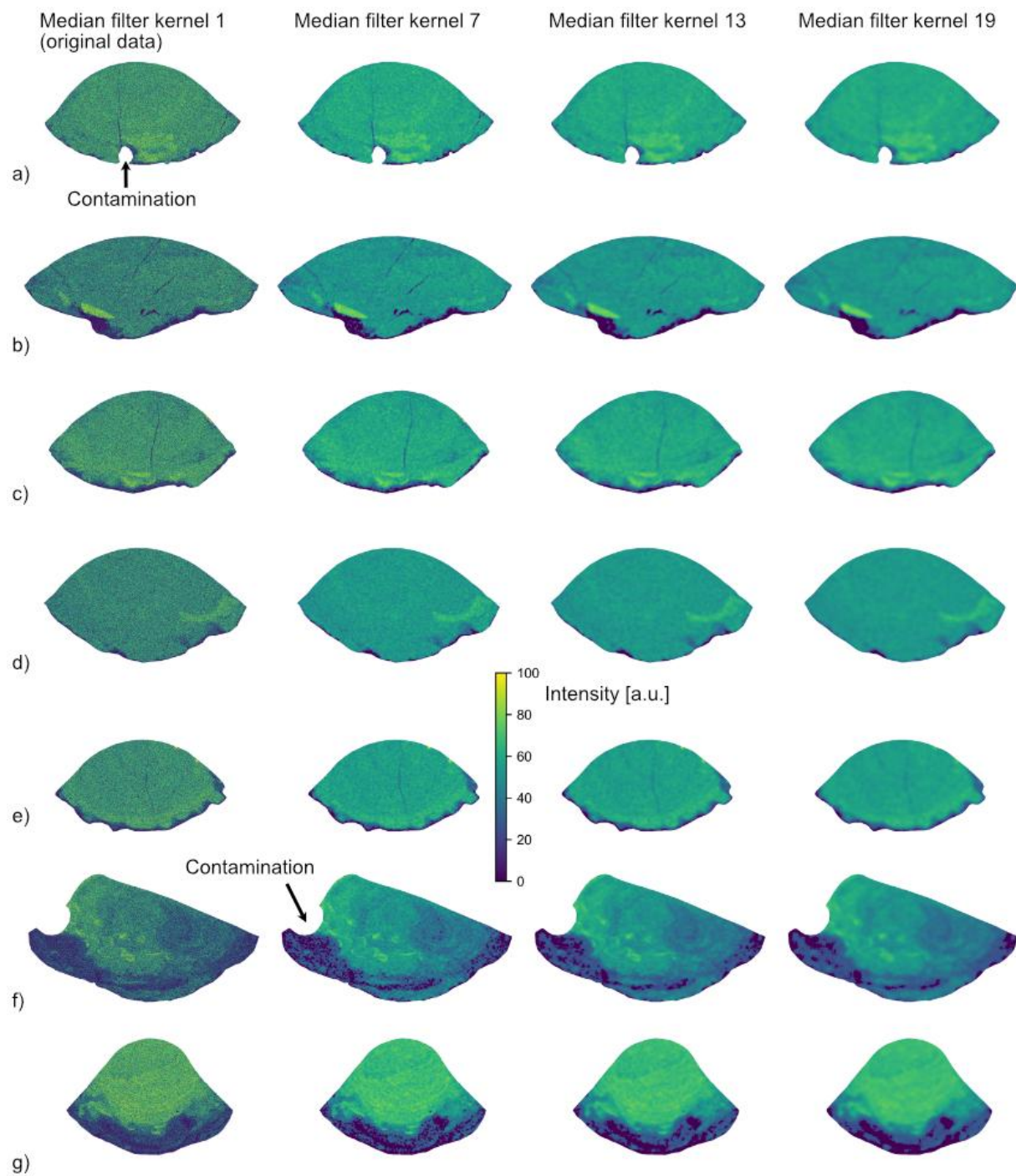


Fig. 17 Images of the EDS data (based on the Cu content) filtered using the median filter and the applied kernel; a) Medusa-shape A1, b) Medusa-shape A2, c) Fish-shape A1, d) Fish-shape A2, e) Concentric circle (a–e front feeding), f) Medusa-shape A2 and g) Fish-shape A1 (back feeding)