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Laser Micro-Wire Cladding: From Fundamental Mechanisms to Application

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Abstract. Laser cladding using thin wires (<0.8 mm) presents significant potential for applications requiring high precision and minimal heat input, such as coatings for nuclear fuel rods. This work investigates Laser Micro-Wire Cladding (LMWC) using a 200 µm wire, showing the transition from fundamental process studies on single tracks and flat substrates to the application of FeCrAl coatings on 15-15Ti and 316L tubes relevant to nuclear fuel rods. High-resolution high-speed imaging (HSI) experiments revealed unique melt transfer characteristics, including a stable melt bridge and drop deposition mode. The mechanisms governing these modes were analysed. A novel wire-bending technique was developed to enhance process stability, crucial for consistent deposition. This understanding facilitated the successful deposition of thin (135 µm), low-dilution (< 7%), defect-free clad layers onto thin (500 µm) substrates. Characterization indicates that the coatings meet demanding requirements for nuclear applications.

1. Introduction

Laser cladding is a versatile manufacturing technique that enables surface modification and repair through localized material deposition using a focused laser beam [1]. While conventional Laser Wire Cladding (LWC) often utilizes wires ≥0.8 mm, Laser Micro-Wire Cladding (LMWC), employing thinner wires, allows for high-resolution features, thin coatings, and minimal heat input into the substrate. This capability is advantageous for demanding applications such as depositing protective layers onto thin-walled nuclear fuel tubes [2], where minimizing the heat affected zone and achieving low dilution and defect free clads are critical requirements.

Downscaling the LWC process to the micro-scale introduces unique challenges as size effects become more pronounced, with surface tension playing a more dominant role relative to gravity compared to conventional LWC [3]. This can influence the behaviour of the melt during processing. Understanding the melt dynamics at this scale is therefore crucial for process stability and ensuring clad quality. Experimental studies of regular-sized LWC typically involve depositing single tracks on flat substrates, followed by overlapping tracks, using specialized high-speed imaging (HSI) cameras to analyse melt transfer and cross-sectional analysis for geometry and dilution assessment [4,5]. Research on LWC using thin (<0.8 mm) laterally fed wires is limited and the melt behaviour requires more investigation. While studies exist that used thin 200 µm wire, they deposited wide tracks (>3 mm) [6,7] or lacked process details [8]. More literature is available for Laser Metal Wire Deposition (LMWD), using thin wires [9,10]. However, LMWD often prioritizes 3D structures and permits higher dilution, and track widths remain relatively large

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(≥440 µm) [10], even with 100 µm thin wires. Narrow tracks require both thin wires and an appropriately sized laser spot diameter. The literature lacks detailed video analysis of the melt transfer in studies applying this specific combination for narrow, low dilution cladding tracks.

This study, therefore, characterizes the melt morphology and its evolution under varying process conditions, exploring the factors influencing deposition stability in LMWC using 200 µm wire and a 290 µm laser. High-resolution HSI revealed unique melt transfer mechanisms distinct from conventional LWC: a stable melt bridge and a non-continuous drop deposition mode. A novel wire-bending technique for enhanced process stability has been introduced.

2. Methods and Materials

A continuous wave IPG Yb-fibre laser (1070 nm) together with a 100 mm focal length collimator and a 150 mm focal length focusing lens defocused to -5 mm were used to achieve a spot diameter of 290 µm. 200 µm diameter wire was fed laterally through a 0.25 mm bore nozzle using a wire feeder. The setup is shown in Figure 1. Argon gas (10-30 l/min) protected the processing zone.

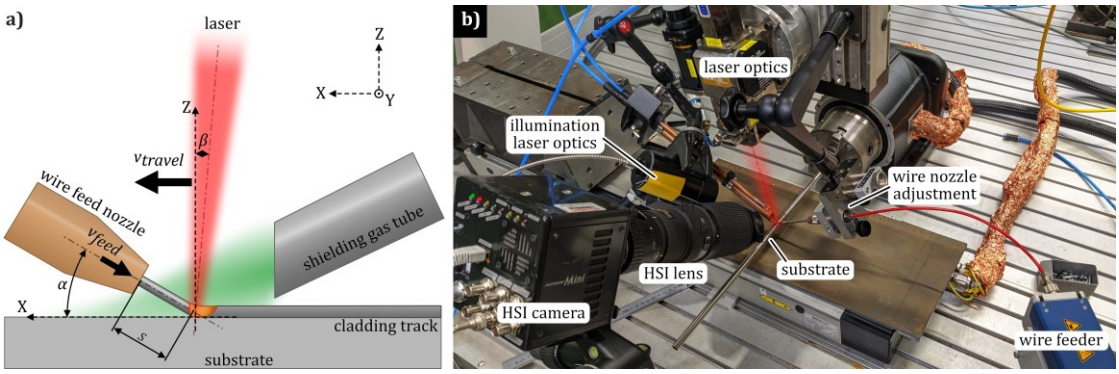

Figure 1. Laser cladding setup schematic a), and photo of the setup for tube cladding in b).

Initial experiments were performed on 2 mm thick AISI 316L plates with ground (Sq ≈ 0.17 µm) and sandblasted (Sq ≈ 2.6 µm) surfaces and 316L and FeCrAl wire. Later experiments involved cladding thin-walled (0.5 mm) 316L and 15-15Ti tubes with an outer diameter of 10 mm with a ground surface (Sq ≈ 0.5 µm) using FeCrAl wires. The chemical composition of the used materials can be found in the supplementary data in table S1.

Process parameters like laser power (P: 80-275 W), travel speed (v_{travel}: 5-25 mm/s), and wire feed speed (v_{feed}: 5-25 mm/s) were varied, and travel and feed speed were kept equal to minimize friction between wire and substrate. Setup parameters like wire angle (α: 30°) and laser angle (β: 5°) were optimized initially. The flat substrate was not cooled during experiments; the tubes were filled with water as a heat buffer to prevent overheating.

A Photron Fastcam mini HSI camera was used, coupled with a Nikon AF 200 mm f/4D ED-IF camera lens, a 50 mm long extension tube, and a Raynox DCR-250 macro converter front lens, giving a resolution of up to 2.5 µm/px at 10,000 fps. A pulsed 808 nm illumination laser and an appropriate bandpass filter were used for illumination.

Track geometric and dilution data were obtained from polished cross-sections using OM and SEM. Dilution was calculated by dividing the cross-sectional area of the substrate by the whole melt, as suggested in the literature [11]. On single tracks, diluton was averaged from two cross-sections, on overlapping tracks at least 10 tracks were measured in a single cross-section. Characteristics of the process will be described with dilution as the main descriptive parameter.

3. Results and Discussion

The investigations revealed a distinct, stable melt transfer mechanism in LMWC, contrasting with the typical melt pool formation described for conventional Laser Wire Cladding (LWC) [1,4,5,12,13]. Instead of spreading widely, the melt formed a bridge suspended between the wire tip and the deposited track, contacting the substrate (Figure 2d), facilitating material transfer from the wire to the track. We attribute this behaviour to three factors inherent to our LMWC setup: 1) The small melt volume of approximately 0.01-0.02 mm^3 (using a 200 µm wire), where surface tension dominates over volumetric forces like gravity. This is 2-3 orders of magnitude smaller than in conventional LWC (using ~1.2 mm wires). The dominance of surface tension likely contributes to the near-cylindrical track cross-sections observed at low dilution (Figure 2a, note the substrate reflections). 2) Highly localized energy input further limits melt spreading. With a laser spot size (290 µm) similar to the wire thickness, most energy is absorbed by the melt bridge, leaving only a small fraction incident on the adjacent substrate. Substrate heating, therefore, occurs mainly via conduction through the melt bridge contact area. 3) Relatively high travel speeds (7.5–20 mm/s) compared to some LWC processes limit the time for significant heat conduction sideways into the substrate. This is supported by the observed independence of track width from travel speed in the tested range, suggesting limited lateral heat spread. The relatively colder surrounding substrate likely hinders spreading [14], consistent with the relatively large wetting angles observed (45–135°), even when significant dilution confirms heat penetration directly below the melt.

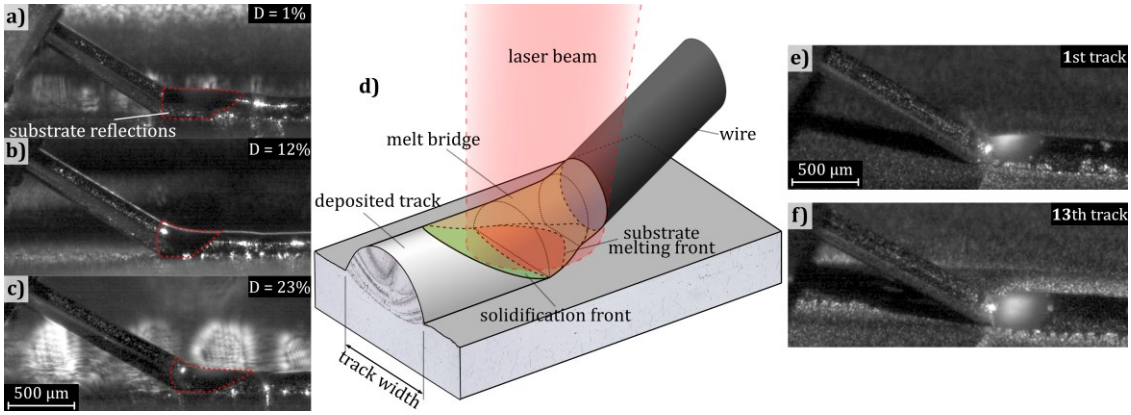

Figure 2. Stable deposition mode facilitating melt transfer through a melt bridge. a)-c) single tracks of increasing dilution D (denoted in figures). d) depiction the melt bridge morphology on a medium (≈15%) dilution track. e)-f) 1st and 13th track of an overlapping track clad.

The melt bridge morphology was sensitive to dilution (Figure 2a-c). Low (<5%) dilution yielded near-cylindrical bridges with limited substrate contact that resulted in nearly circular track cross-sections. Conversely, high dilution (>20%) bridges flattened into wider, semi-circular cross-sections, increasing wetting and contact width but, counter-intuitively, decreasing the contact length between melt and substrate along the track (Figure 2c). Despite comparable melt volumes across dilutions, it is assumed that the greater contact width in high-dilution cases enhances heat dissipation into the substrate, promoting faster solidification onset and thus shortening the contact length. Even with this increased wetting, the resulting tracks remained remarkably narrow (220–370 µm), exceeding the laser spot size only slightly at high dilution but representing, to our knowledge, the narrowest LWC tracks reported. This highlights the fundamentally different melt transfer characteristics of LMWC caused by the melt bridge. When

transitioning from single to overlapping tracks, the morphology of the melt bridge changed noticeably (Figure 2e-f). The bridge is partially supported by the previous track and takes a more traditional pool-like shape with a less convex surface. While melt or liquid bridges are mentioned in hot wire laser welding [15], laser hot-wire cladding [16], or laser wire deposition [17], they are typically described as connecting the wire tip to a pre-existing, distinct melt pool. In contrast, HSI observations in LMWC suggest that the melt bridge can supplants the melt pool entirely.

The melt transfer was occasionally interrupted by a melt bridge collapse. It involved the bridge partially lifting from the substrate, stretching, necking near the wire tip, and separating into two droplets. Using laser speckle tracking to measure wire feed velocity, these collapses were linked to wire feed instabilities (e.g., tension release/build-up). Specifically, a distinct surge in actual wire feed speed occurred just before collapse, increasing the melt volume (confirmed by increased track height pre-collapse) and likely causing cooling of the melt. This was immediately followed by a decrease in feed speed, coinciding with the stretching and collapse the melt bridge.

A consequence of collapse is the potential drop deposition mode initiation. This mode is characterized by a periodic deposition of drops (supplementary data, Video 1). Two distinct mechanisms were identified, shown in Figure 3. In direct absorption (Video 1c), the laser is directly absorbed by the wire end and later the melt droplet. The melt droplet forms as the wire end intersects the laser beam mid-air (Figure 3 a1), causing the wire to melt. The droplet grows continuously (a2-a4) as more wire is fed into the laser until the size of the droplet reaches a limit where it contacts and adheres to the substrate. Upon moving, the wire disconnects from the attached drop, and the cycle repeats. During reflection absorption (video 1a), the laser beam reflects off a previously deposited droplet (Figure 3 b1), focusing energy onto the wire tip (b2). This melts the wire (b3), forming a new droplet on the wire tip, which grows and moves towards the wire feeding nozzle (b4). The reflections then get out of alignment, and the wire moves the droplet towards the substrate, until it contacts and adheres to it. The deposited droplet becomes the new reflective surface, repeating the cycle. To verify this, HSI footage was analysed and droplet volume and key geometric angles relating to the reflective surface, laser path, and wire position were calculated. Detailed schematics can be found in the supplementary data, Figure S1.

Often a combination of direct and reflection absorption was observed. An example can be seen in Video 1b. There, reflected absorption first causes the formation of an initial droplet that further grows through direct absorption. Size and spacing of the drops were found to be governed by the ratio of direct/reflection absorption. Reflection absorption leads to narrowly spaced, small drops while direct absorption results in larger, broad spaced drops. The ratio can be controlled

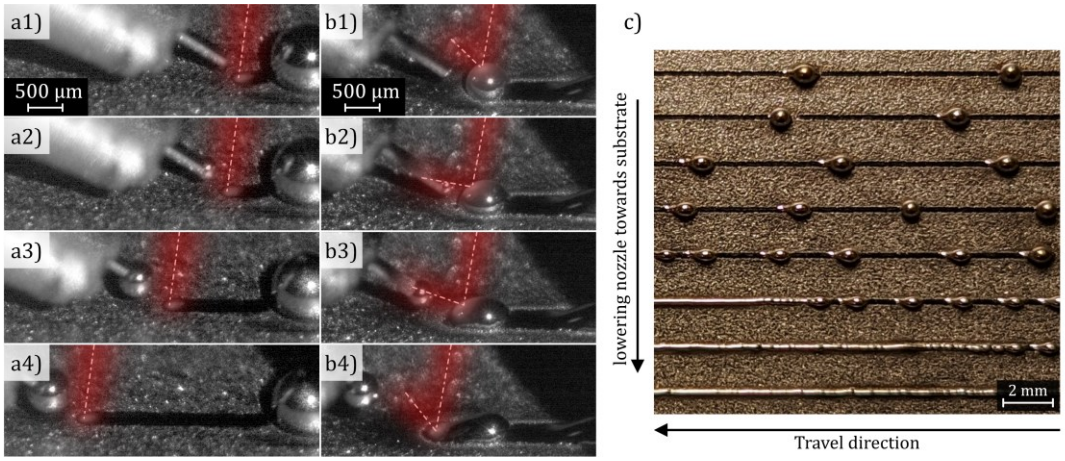

Figure 3. Drop deposition mode based on a) reflection absorption, b) direct absorption. c) Influence of lowering the nozzle towards the substrate on drop size and frequency.

by changing the nozzle – substrate distance. As shown in figure 3c, lowering the nozzle transitioned from far spaced, large drops (direct absorption) to narrowly spaced, smaller drops (reflection absorption), until finally, a stable melt bridge facilitated a continuous deposition.

Prerequisite for drop deposition was the absence of a stable melt bridge. Either the melt bridge collapsed or the nozzle – substrate distance was too large, preventing a melt bridge from forming. Liu et al. [4] described a drop deposition mode using laterally fed 0.89 mm wire that occurred when the wire tip was oriented towards the rear of the melt pool, which agrees with our findings. However, a drop deposition based on laser reflections using 200 µm thin wires, with the possibility to fine tune drop size and spacing, seems not to be described in the literature yet.

Our investigations revealed that inconsistencies in wire feeding and the melt bridge losing contact with the substrate were the primary causes of instability. To address this, a novel "wire-bending" technique was developed [3] that forces a bend in the wire during deposition as shown in Figure 4. High-speed imaging (HSI) confirmed that this bend ensures continuous contact between the wire tip and the substrate. This stabilizes the wire end position, particularly in the vertical (Z) direction, preventing the melt bridge from lifting off the substrate. Furthermore, the bending likely improves positioning accuracy in the lateral (Y) direction by centring the wire within the feeding nozzle bore. Consequently, the wire-bending technique significantly mitigates melt bridge collapses and improves overall process stability, leading to more consistent tracks. This deliberate use of wire-bending to censure wire/substrate contacts contrasts with some literature that views such contact negatively [12,13].

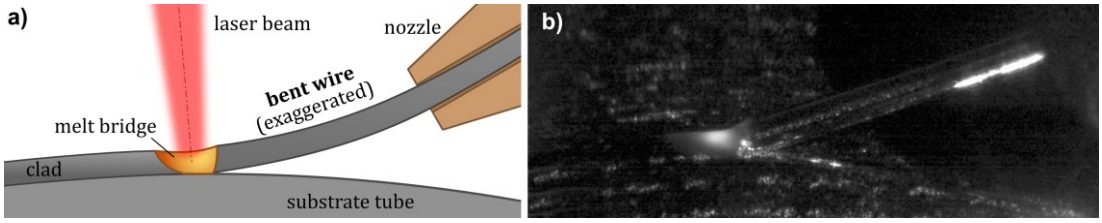

Figure 4. Wire-bending technique a) exaggerated sketch, b) HSI still frame exhibiting a slight bend.

With the expertise gained on flat substrates, thin-walled tubes made of 15-15Ti and 316L were cladded with FeCrAl in a spiralling motion, with 250 µm track spacing (Figure 5). Both combinations yielded successful clads with 135 µm layer thickness (in the valleys) and 6-7% dilution. No porosity or defects, and only infrequent, minor lack of fusion pores at the interface were observed. Wire-bending was successfully used to counteract the runout of the tube in the rotation device and the out-of-roundness of the tube itself.

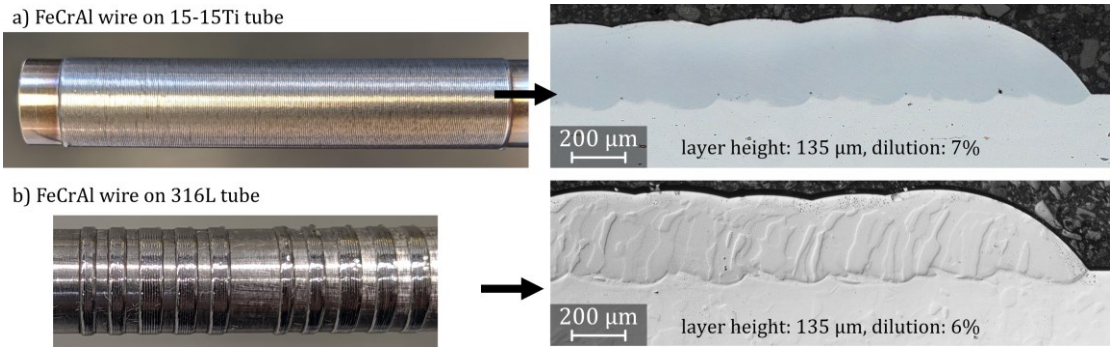

Figure 5. Successful FeCrAl clads on nuclear fuel tubes and their respective cross-sections.
a) 15-15Ti substrate, b) 316L substrate.

4. Conclusions

High-resolution HSI gave new insights into the melt transfer in laser wire cladding (LWC) at the micro scale. A new melt bridge type was discovered facilitating melt transfer. It can transition to a more traditional melt pool on overlapping tracks or single tracks of higher (>20%) dilution. A novel wire-bending technique improved process stability by stabilizing wire end position during deposition and maintaining contact between wire and substrate. The capabilities of Laser micro wire cladding (LMWC) using 200 µm wire and a 290 µm laser spot were demonstrated by producing thin (135 µm) clads with low (6-7%) dilution.

Acknowledgements

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