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Procedia CIRP 143 (2026) 420–423

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14th CIRP Conference on Photonic Technologies

Experimental and CFD Analysis of Core–Ring Beam Shaping for Near-Infrared Copper Hairpin Welding

Gajarajan Sivayogan[a,*], Paul Butler-Smith[a], Mikdam Jamal[a], Annie Kerwin[a], Mitchell Leering[a], Heather Nute[a], Jakob Terry[a], Giulio Borzoni[b], Daniele Nocciolini[b], Sundar Marimuthu[a]

[a)] *Manufacturing Technology Centre (MTC), Ansty Park, Coventry, CV7 9JU, United Kingdom*
[b)] *IMA EV-TECH, Strada S. Appiano 8/A - 50028 Barberino Tavarnelle - Italy*

* Corresponding author. Tel.: +44 (0) 24 7670 1600; *E-mail address:* gajarajan.sivayogan@the-mtc.org

Abstract

Copper hairpin welding is widely used in the manufacture of electric drive systems, yet the process remains sensitive to variations in positioning, surface condition, and energy distribution. This study combines experimental trials with melt pool simulation to investigate how near infrared beam-shaping strategies influence copper hairpin welding. Experiments were carried out using a near infrared fibre laser with controlled core and ring power splits. Adding a small outer-beam component, rather than using a fully core-focused beam, reduced porosity and improved weld robustness, with the 5% ring condition giving the clearest improvement over the 100% core baseline. A three-dimensional melt pool model developed in FLOW-3D reproduced the main weld bead dimensions with errors below 10% and matched the expected scaling behaviour observed in the literature. The work provides two contributions: the combined use of high-fidelity computational modelling with experimentally validated near infrared beam shaping, and new evidence on the sensitivity of weld quality to power distribution. Together, the modelling and experimental results establish a workflow that can reduce physical trial requirements and support the development of advanced absorption-enhanced and beam-shaped welding strategies for industrial copper hairpin manufacture.

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Peer-review under responsibility of the scientific committee of the 14th CIRP Conference on Photonic Technologies [LANE 2026]

Keywords: Copper hairpin welding; Near infrared laser; Beam shaping; Core–ring power distribution; Melt pool modelling; Porosity reduction

1. Introduction

Laser welding of copper hairpins is a critical step in traction motor manufacture, where the reliability of hundreds of joints directly influences electrical and mechanical performance. Instability in the process can lead to porosity, spatter, or incomplete fusion, making robust quality monitoring essential [1]. Industrial systems predominantly use near infrared fibre lasers between 1060 and 1080 nm, but copper reflects most near infrared energy at room temperature and conducts heat rapidly. These properties make weld quality highly sensitive to positioning, surface condition, gap, and local temperature, as widely reported in near infrared hairpin welding studies [2, 4, 6].

Absorption increases sharply as copper heats and melts, and the transition to keyhole mode introduces transient melt pool behaviour that can promote porosity formation. Prior work has therefore focused on mitigating instability through process window optimisation, elongated beams, beam oscillation, and modified intensity distributions to control melt flow [4, 6]. Beam shaping, particularly approaches that distribute energy between a central core and a lower intensity outer ring, has been shown to broaden the keyhole opening, moderate peak intensity, and reduce porosity in copper welding [2, 4]. However, the effect of controlled intensity redistribution on weld robustness in industrial hairpin geometries is still not well understood.

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10.1016/j.procir.2026.07.088

Although copper absorption increases at shorter wavelengths, in practice most industrial hairpin systems still rely on near infrared laser sources due to their maturity, high power availability, and compatibility with high-speed automation. Consequently, improvements in process stability often rely on modifying the spatial distribution of near infrared beam rather than changing wavelength. Beam shaping therefore represents a practical and scalable route for enhancing melt pool stability without requiring alternative laser sources.

This study evaluates how specific core-to-ring power distributions influence porosity, bead geometry, and stability in near infrared laser hairpin welding, supported by high fidelity computational modelling. A transient three-dimensional melt pool model was developed and implemented in FLOW-3D to assess how variations in absorbed energy and beam shape influence melt flow within the hairpin geometry, following methodologies established in contemporary copper hairpin modelling and benchmarking work [10, 11]. The objectives are threefold. The first is to quantify the effect of core-ring power splits on weld robustness across industrial hairpin geometries. The second is to evaluate how these trends correspond to melt pool behaviour predicted by the computational model. The third is to establish a combined experimental and simulation workflow that reduces physical trial requirements and supports the development of stable and repeatable beam-shaped welding strategies for copper hairpin manufacture.

2. Methodology

2.1. Experimental Setup

Commercially available enamel coated copper wire was used for all trials. Four rectangular cross-sectional geometries were tested, with typical dimensions between 3.55 × 1.78 mm and 4.0 × 2.5 mm. The polyester enamel coating had an average thickness of approximately 64 µm ± 10 µm , measured across multiple samples.

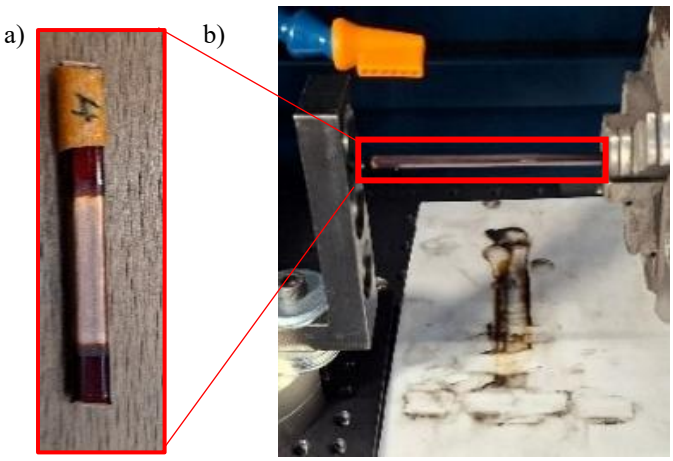


Fig. 1. Copper hair pin stripping preparation set up (a) copper hair pin (b) Copper hairpin fixture.

Prior to welding, the enamel was removed over a sufficient length to expose the copper substrate. Stripping was carried out using nanosecond pulsed IR laser processing on a GF P400 system, (Average power 26 W, pulse duration 200 ns, horizontal raster, scan speed 1 m/s, 30 kHz, 50% spot overlap, 10 µm hatch distance) which ablated the coating without damaging the underlying copper. The stripped ends were then filed manually to produce a flat and clean surface for joining.

Figure 1 depicts the enamel stripping setup. Fixturing was performed using a vice or locking pliers to position pairs of hairpins in close contact. The accuracy is critical to avoid porosity; a maximum allowed gap of 0.1 mm and a maximum lateral offset of 0.5 mm were used, based on established best practice for hairpin welding.

All welding trials were conducted using a Trumpf TruDisk 8000W fibre laser integrated with a PFO 33 galvoscanner. The system operates at a wavelength of 1030 nm and provides independent control of core and ring intensity distributions through a two in one beam delivery arrangement. No shielding gas was used, in line with the industrial requirment.

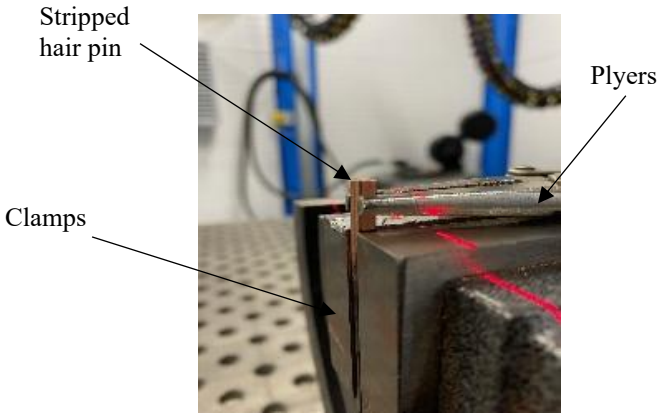


Fig. 2. Copper hair pin experimental rig setup.

A series of experiments was conducted to evaluate the influence of core to ring power distribution on weld formation and porosity. The baseline condition used one hundred percent of the power in the core. Welded samples were sectioned and polished to reveal the central cross section of the joined pair. Etching was performed following standard metallographic practice. Microscope images were captured for bead width, height, and penetration depth quantification. Porosity levels were measured using ImageJ, an open-source image-analysis software, by isolating voids through thresholding and calculating the void area fraction within the weld bead.

Table 1 outlines the process parameters investigated in the experimental study. All welds were performed at the focal position of the laser, using four power-distribution settings that shifted a small fraction of power from the central beam to an outer region. These ranged from 100% core to 85% core in steps of 5%.

Table 1. Summary of the experimental input conditions used for copper hairpin welding trials.

Parameter	Value
Laser Power	5 kW
Spot Size (Core/Ring)	155 µm / 560 µm
Pulse Duration	36 ms
Speed	300 mm/s
No. Loops (Repetitions)	4
Scan size	4 mm x 2.1 mm

2.2. CFD Setup

A three-dimensional transient melt pool model was developed in FLOW-3D to simulate copper hairpin welding under near infrared laser illumination. The physics models activated included heat transfer in solid and liquid regions, phase change using an enthalpy formulation, free-surface tracking, surface tension and Marangoni effects, and optical absorption based on Fresnel reflectivity. Together, these models allow prediction of melt pool shape, fluid movement, and transient thermal behaviour.

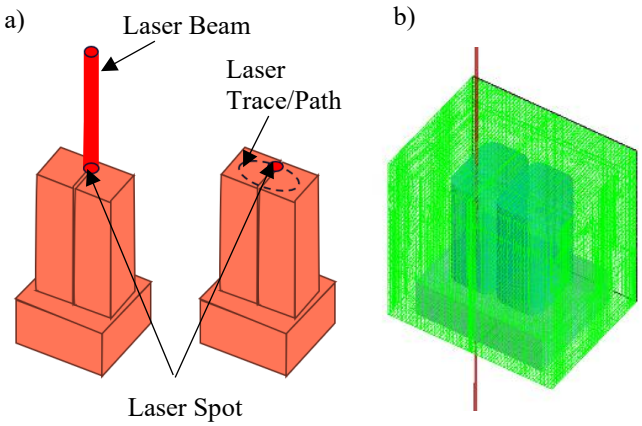


Fig. 3. Copper hairpin welding setup: (a) schematic showing the laser beam, laser spot, and scan path; (b) corresponding CFD domain and mesh.

The geometry of two hairpins was reproduced in simplified form, with a copper block incorporated to represent the fixture supporting the samples. The enamel coating was not included in the model, as its thermal contribution is minor compared with the bulk copper substrate. A custom MATLAB-based beam profile generator was implemented to approximate both Gaussian and core–ring intensity distributions. The standard deviation and peak intensities were selected to match the laser spot dimensions defined experimentally. Absorption coefficients and thermal properties followed values typical for near infrared copper welding reported in literature. The model was verified against experimental data from [5] by comparing melt pool width, height, and thickness. The predicted results were within 1% of the experimental width and height, with a larger deviation in thickness attributed to absorption uncertainty, Table 2 outlines the specific modelling inputs used in the computational analysis. The chosen hairpin geometry for the model was 2.66 mm by 3.87 mm, and all laser parameters were taken directly from the experimental conditions listed in Table 1.

Table 2. Summary of the experimental input conditions used for copper hairpin welding trials.

Parameter	Value
Core Power	100%
Mesh Resolution	100 µm
Beam Profile	Gaussian
Shield gas	off
Fresnel Constant	0.1

3. Results

3.1. Experimental Results

This section presents the experimental findings obtained using the copper hairpin geometries, process parameters, and beam shaping conditions defined in Table 1. The 100% core condition produced welds with a rough crown appearance and visible surface irregularities. Manual pull testing showed that these welds separated easily, indicating weak joint formation. Microscopy confirmed the presence of significant porosity, with several large voids located near the upper part of the weld bead. Introducing a ring component led to immediate improvements. Using a 5% ring condition, the welds exhibited smoother crown formation and much higher resistance to manual separation. Cross-sectional analysis of a representative weld showed a porosity level of 4.17%. The pores were large and unevenly distributed, indicating unstable melt pool behaviour. The introduction of 5% ring reduced porosity substantially to approximately 1.7%. The 10% and 15% ring cases produced fewer large pores than the baseline, although total void area varied.

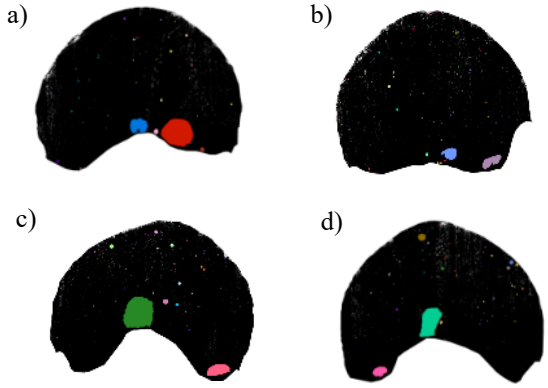


Fig. 4. Porosity section cut measurements a) 100% b) 95% c) 90% and d) 85% Core Power.

Overall, the addition of a ring component reduced the occurrence of large defects relative to the 100% core condition. Bead width for all cases ranged between 5.3 mm and 5.6 mm, while bead height ranged from 3.4 mm to 4.6 mm. These values align with the expected effect of distributing energy more evenly across the scan path.

The experimental results demonstrate that the use of a ring component increased process stability without changing total power or scan speed. Preliminary manual pull testing and microscopic inspection indicated that using a small fraction of the power in the ring significantly improved weld strength and reduced porosity. These trends highlight the value of beam shaping for moderating peak intensity and promoting steadier melt behaviour in copper hairpin welding.

3.2. Simulation Results

This section summarises the predictions produced using the FLOW-3D Weld melt pool model with the inputs listed in Table 2. The model generated a stable melt pool along the elliptical scan path, with a keyhole cavity formed through recoil-pressure-driven vapour generation. The temperature distribution showed a typical peak at the forward region of the melt pool, directly beneath the laser travel direction, with a continuous gradient into the surrounding copper. Across the four elliptical loops, the melt pool shape and temperature fields showed broadly similar behaviour, indicating that the applied absorption parameters and physics models were suitable for this process regime. Applying the industrial parameters outlined in Table 1 and 2, the model produced bead widths, bead heights, and penetration thicknesses within 10% of the experimental measurements provided for the reference production welds. Although the simulated bead shape was narrower and slightly deeper than the micrographs, the overall magnitude of the dimensions was comparable. This deviation was attributed to two known uncertainties:

- the scaled absorption factor (1.35×), and
- the approximate Gaussian beam representation, used in the absence of an intensity map.

Despite these limitations, the results showed that the model can reliably capture the key geometrical features of hairpin welds.

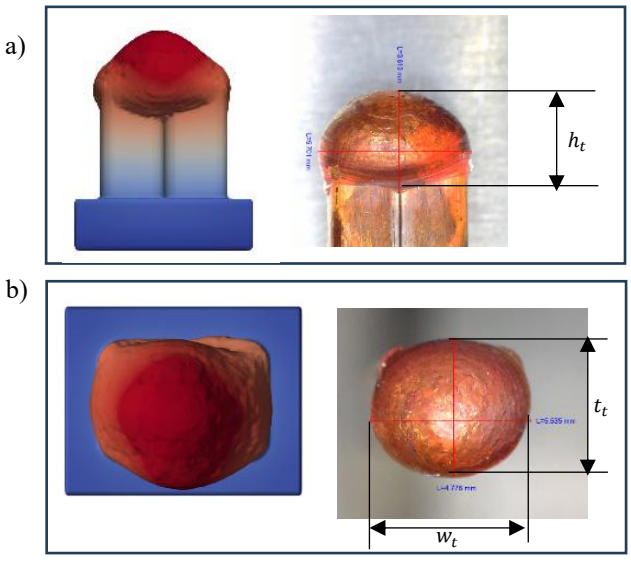


Fig. 5. Flow-3D CFD modelling results for 100% Core 0% Ring. From left to right Simulated vs Experimental a) Side b) Top View.

Table 3. Results from the 100% Core 0% Ring beam.

Case	h_t	t_t	w_t
Experiment [mm]	3.81	4.78	5.54
Model [mm]	3.54	4.46	5.36
Error (%)	7.86	6.97	3.32

4. Conclusion

This study combined experiments and computational modelling to investigate the influence of core-to-ring beam shaping on copper hairpin welding using a near infrared fibre laser. The experiments showed that introducing a small ring component reduced porosity and improved weld robustness, with the 5% ring condition giving the clearest improvement over the 100% core baseline. The FLOW-3D melt pool model reproduced weld bead dimensions within 10% of measured values and captured the main trends in melt pool behaviour observed in the experimental results. Together, the modelling and experimental work establish a practical workflow for assessing the effect of spatial energy distribution on melt stability in copper hairpin welding. This combined approach reduces physical trial requirements and supports the development of stable, repeatable, beam-shaped welding strategies for industrial copper hairpin manufacture.

5. Acknowledgements

The Authors gratefully acknowledge the Horizon Europe programme under the grant agreement 101138380 – FLASH in association with IUK for funding this work.

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