

AN EXPERIMENTAL STUDY OF COMBINED SPIRAL-ELLIPTICAL SCANNING TRAJECTORIES FOR BLUE LASER WELDING OF COPPER HAIRPIN WIRES IN ELECTRIC MOTOR STATORS

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Abstract - Blue laser welding at a wavelength of 450 nm overcomes the limited infrared absorptivity of copper but still requires a suitable scanning trajectory to compensate for hairpin assembly misalignment. This study experimentally evaluates a combined Spiral-Elliptical scanning strategy for blue laser welding of Cu-ETP copper hairpins with a cross-section of 2.0×2.2 mm across twelve conditions of laser power ranging from 600 to 760 W and scanning speed ranging from 25 to 35 mm/s. The results show that penetration depth, rather than weld width, governs weld quality: the weld width remains stable at 4.3 to 4.9 mm, while the penetration depth increases with power, and the welds meet both quality criteria only at 680 W. Four samples welded at 680 W achieved failure loads of 323 to 450 N and contact resistances of 30 to 60 $\mu\Omega$, with elliptical scanning speed governing the trade-off between tensile strength and contact resistance.

Key words - Blue laser welding; Copper hairpin; Spiral-Elliptical trajectory; Penetration depth; Contact resistance

1. Introduction

The development of the electric vehicle (EV) industry is driving the demand for electric motors with increasingly high efficiency and power density [1–7]. In this context, hairpin stator windings using solid rectangular copper conductors are gradually replacing conventional round-wire winding methods owing to their higher slot fill factor, improved heat dissipation capability, and enhanced power density. Depending on motor size, a stator may contain 160–220 pairs of hairpin ends that require both electrical and mechanical joining [6, 8]. The quality of each weld directly determines the reliability of the entire system, as a defective joint may cause a short circuit or shorten the motor lifetime [2, 3, 9, 10].

Due to the highly limited working space at the winding end, laser beam welding (LBW) has become a preferred method because of its non-contact heating capability, high energy density, and ease of automation [8, 11, 12]. However, pure copper has very high thermal conductivity and extremely low optical absorptivity for infrared laser radiation (IR/NIR, wavelength of approximately 1000 nm), only about 5% at room temperature [11, 13]. This requires IR lasers to operate at kilowatt-level power to maintain the keyhole mode [9, 14, 15]. The high-energy keyhole mode in copper is inherently unstable and is prone to spatter, melt pool collapse, and porosity [16, 17].

Blue diode lasers, with a wavelength of approximately 450 nm, directly overcome this limitation: the absorptivity

of solid copper for blue laser radiation reaches 60–65%, which is much higher than that for IR lasers [11, 18, 19]. As a result, melting occurs stably in conduction mode without the need to form a deep keyhole, thereby eliminating most spatter and porosity phenomena [16, 20].

Nevertheless, geometric errors arising from the bending, insertion, and assembly of hairpins still generate gaps and height differences between the two wire ends [21, 22]. With a linear scanning trajectory or a stationary laser spot, the laser beam can easily pass through the gap, damage the underlying insulation layer, and fail to provide sufficient molten material to bridge the gap. Elliptical, circular, and spiral scanning trajectories have shown better capability in directing heat flow, distributing energy uniformly, and prolonging the lifetime of the melt pool [7, 23, 24]. A staged scanning strategy - in which the spiral trajectory gradually heats each hairpin leg so that the molten metal flows into and bridges the gap, followed by an encompassing elliptical trajectory to fully fuse the two legs - shows promise for simultaneously optimizing gap filling and thermal stability without creating local energy hot spots at sharp turning points of the trajectory.

On this basis, this paper presents an experimental investigation of blue laser welding of copper hairpin wires using a combined Spiral-Elliptical scanning trajectory strategy. The objective is to quantitatively determine the effects of laser power and scanning speed on the geometric dimensions of the weld, including weld width and penetration depth. From these results, an optimal process parameter window is established and validated through mechanical testing and contact resistance measurements, providing a reliable technical basis for controlling the quality of hairpin connections in electric motor production for electric vehicles.

2. Experimental methods

2.1. Materials and blue laser welding system

The experimental material was high-purity Cu-ETP copper hairpin wire with a cross-section of 2.0×2.2 mm, which is representative of conductors used in stator windings for electric traction motors. The welding system employed a continuous-wave (CW) blue diode laser with a wavelength range of 420–480 nm, integrated with a Raylase SS-IV-30 V3 galvanometer scan head that enabled high-speed beam deflection and precise trajectory control. The laser power was adjustable within the range of 600–760 W. The focusing optics produced a beam spot

with a diameter of approximately 475 μm on the hairpin surface. Figure 1 illustrates the welding system and the actual hairpin stator sample used in this study.

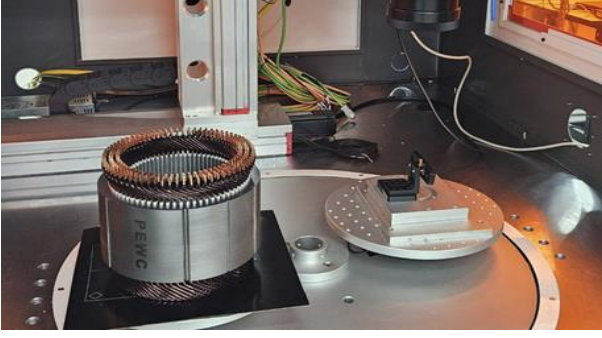


Figure 1. Blue laser welding system and experimental copper hairpin stator sample

Throughout the welding process, high-purity argon was supplied as the shielding gas to limit oxidation of the molten copper and minimize porosity and oxide formation in the weld [3, 22]. All process parameters, including laser power, scanning speed, trajectory amplitude, and shielding gas flow rate, were calibrated in advance and kept constant for each experimental condition to ensure repeatability.

2.2. Design of the Spiral–Elliptical scanning trajectory

The scanning trajectory consisted of four consecutive segments, namely Spiral 1, Spiral 2, Elliptical 3, and Elliptical 4, which were continuously programmed on the scan head in the fixed sequence of Spiral 1 $\rightarrow$ Spiral 2 $\rightarrow$ Elliptical 3 $\rightarrow$ Elliptical 4, as shown in Figure 2. The two spiral segments were positioned at the two opposite ends of the hairpin, concentrating energy to promote stable melting and enhance local wetting, thereby allowing the molten metal to flow into and bridge the assembly gap. The two nested elliptical segments in the central region were repeated multiple times to cover and fully fuse the two hairpin legs into a continuous joint, while avoiding the formation of energy hot spots at trajectory turning corners.



Figure 2. Spiral–Elliptical scanning trajectory:
(1) Spiral 1, (2) Spiral 2, (3) Elliptical 3, (4) Elliptical 4

Mathematically, the elliptical segments are described by the following system of equations:

$$\begin{cases} x(t) = a \cos(t) \\ y(t) = b \sin(t) \end{cases} \quad \text{with } t \in [0, 2\pi] \quad (1)$$

where, a and b are the semi-major and semi-minor axes along the x and y directions, respectively.

The spiral segments represent elliptical motion with a gradually expanding radius and are described by the following system of equations:

$$\begin{cases} x(\theta) = (a + b\theta) \cos(\theta) \\ y(\theta) = (c + d\theta) \sin(\theta) \end{cases} \quad (2)$$

where, θ is the angular parameter, a and c are the initial radii, and b and d are the radial expansion rates along each axis.

These parameters were programmed directly in the scan

head control software, including the radius, spiral pitch, rotation direction, and elliptical ratio for each segment, ensuring that the trajectory executed by the welding system matched the theoretical design. Table 1 lists the geometric parameters and actual number of repetitions for each segment.

Table 1. Geometric parameters and number of repetitions for each trajectory segment

Parameter	Spiral 1	Spiral 2	Ellip. 3	Ellip. 4
Size (mm)	0.6×0.3	0.6×0.3	1.5×0.1	3×0.2
Center position (mm)	(1.2;0;0)	(-1.2;0;0)	(0;0;0)	(0;0;0)
Number of repetitions	1	1	6	4

The size values in Table 1 represent the maximum envelope dimensions of the trajectory. For the elliptical segment, the size is given by $2a \times 2b$ according to Equation (1). For the spiral segment, the size is given by $2(a + b\theta_{\max}) \times 2(c + d\theta_{\max})$ according to Equation (2), where $\theta_{\max}$ is the scanning angle corresponding to the final repetition of each segment.

2.3. Welding experimental matrix

The welding matrix comprised 12 cases, numbered from 1 to 12, designed using three laser power levels of 760, 680, and 600 W in combination with two scanning speed configurations: 25 or 30 mm/s for the two spiral segments and 30 or 35 mm/s for the two elliptical segments, as presented in Table 2. The assembly gap of each specimen, measured using image measurement software, ranged from 210 to 569 μm (Table 2), which allowed the adaptability of the Spiral–Elliptical trajectory to large geometric deviations to be evaluated.

Table 2. Experimental parameter matrix for blue laser welding using the Spiral–Elliptical trajectory

Case	P (W)	Spiral (mm/s)	Ellip. (mm/s)	Gap (μm)
1	760	25	35	357
2	760	30	35	569
3	760	25	30	482
4	760	30	30	256
5	680	25	35	210
6	680	30	35	359
7	680	25	30	496
8	680	30	30	365
9	600	25	35	236
10	600	30	35	498
11	600	25	30	423
12	600	30	30	312

2.4. Weld quality evaluation method

Each weld was sectioned, ground, and polished for cross-sectional imaging, from which the weld width and penetration depth were measured using image measurement software. The mechanical performance of the joint was evaluated by a tensile-shear test on a lap-joint specimen consisting of two welded hairpin wires, as shown in Figure 3 [6, 11]. The test was performed using a Shimadzu AGS-X testing machine equipped with a 5 kN load cell at a crosshead speed of 1.0 mm/min. Three specimens were tested for each welding condition. The width and depth values in Tables 3 and 4 were measured from one representative cross-section for each

condition. The variation among specimens under the same welding condition was 0.05–0.15 mm, which was attributed to hairpin clamping during welding and to assembly tolerances in gap and width.

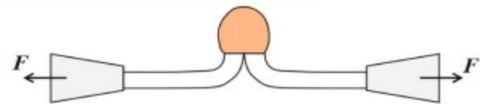


Figure 3. Schematic of the tensile-shear test configuration for welded copper hairpin joints

The electrical contact resistance was determined using the four-point Kelvin probe method, as shown in Figure 4 [6, 11]. A current of 10 A was supplied through the two outer probes (I_1 , I_2), while the voltage drop was measured through the two inner probes (U_1 , U_2). This configuration eliminated the resistance of the lead wires and probes, thereby enabling accurate determination of the resistance at the welded interface, denoted as R_{measure} . The measurement was conducted using an MO-2014 micro-ohmmeter with a resolution of 1 $\mu\Omega$ and a measurement range of up to 60,000 $\mu\Omega$. Three specimens were measured for each condition to ensure statistical reliability.

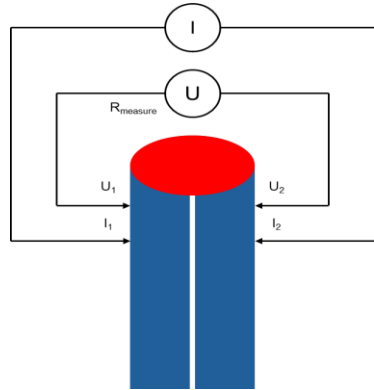


Figure 4. Schematic diagram of contact resistance measurement using the four-point Kelvin probe method

3. Results and discussion

3.1. Experimental weld morphology

Figure 5 presents overview photographs of the weld surfaces of copper hairpin samples after blue laser welding using the Spiral–Elliptical trajectory.



Figure 5. Surface photographs of the welds on copper hairpin samples after blue laser welding using the Spiral–Elliptical trajectory

The weld beads were formed continuously and uniformly among the samples, with a smooth rounded profile at the top of the joint. No spatter, surface cracking, or off-center burning was observed, which is consistent with the characteristics of stable melting in conduction mode during blue laser welding. The quantitative weld dimensions, including width and penetration depth, were determined by cross-sectional measurements for each welding condition and are presented in detail in Section 3.2.

3.2. Effects of laser power and scanning speed on weld dimensions

Table 3 presents the measured weld width and penetration depth corresponding to the twelve welding conditions listed in Table 2.

Table 3. Experimental weld width and penetration depth for each welding condition

Case	P (W)	Width (mm)	Depth (mm)	Classification
1	760	4.85	4.18	Excessive
2	760	4.75	3.89	Excessive
3	760	4.78	3.77	Excessive
4	760	4.67	4.02	Excessive
5	680	4.56	2.89	Acceptable
6	680	4.62	2.76	Acceptable
7	680	4.57	2.95	Acceptable
8	680	4.39	2.76	Acceptable
9	600	4.45	2.12	Insufficient
10	600	4.37	1.95	Insufficient
11	600	4.31	1.98	Insufficient
12	600	4.51	2.16	Insufficient

The data in Table 3 reveal a clear trend: the weld width remained relatively stable over the entire investigated power range, varying within a narrow range of 4.31–4.85 mm, whereas the weld depth varied strongly with laser power. The average weld depth was 3.97 mm at 760 W, decreased to 2.84 mm at 680 W, and further decreased to 2.05 mm at 600 W. In other words, within the investigated parameter range, penetration depth, rather than weld width, was the dominant criterion governing weld quality classification. At 760 W, the high linear energy input caused the penetration depth to exceed the target threshold, above 3.5 mm, creating a risk of excessive penetration. At 600 W, the energy input was insufficient to reach the minimum penetration depth of 2.5 mm, resulting in insufficient penetration. Only at 680 W did the penetration depths of all four scanning-speed combinations fall within the target range of 2.5–3.5 mm.

Notably, at the laser power of 760 W, the Spiral–Elliptical trajectory still produced a fully fused joint even when the assembly gap reached 569 μm , as in Case 2, with a width of 4.75 mm and a depth of 3.89 mm. This result directly demonstrates the role of the two spiral segments in guiding the molten metal to flow into and bridge large gaps before the elliptical segments fully fuse the two hairpin legs. It therefore confirms the robustness of the combined scanning strategy against practical assembly deviations. The effect of scanning speed within each power level was secondary compared with that of laser power. At 680 W, the difference in penetration depth among the four speed combinations, from 2.76 to 2.95 mm, was only approximately 0.2 mm, indicating that the 680 W power window has good tolerance to scanning-speed variations within the range of 25–35 mm/s.

3.3. Quality criteria and comparison with infrared laser welding

The weld width determines the bonding area and electrical conduction capability of the joint, whereas the weld depth determines structural integrity. Insufficient depth may lead to an open electrical circuit or mechanical separation during operation, while excessive depth increases

the risk of keyhole instability, spatter, and porosity. To place these results in context, the present results are compared with published infrared (IR) laser welding data for the same type of copper hairpin wire. Dimatteo *et al.* reported welds produced at 1500–2500 W with a width of 3.0–4.0 mm, a depth of 2.0–3.0 mm, and a cross-sectional area exceeding approximately 7.0 mm² [25]. Yu *et al.* reported welds produced at 2400–2700 W with a width of 4.4–4.6 mm, a depth of 3.3–3.6 mm, and an area of approximately 8.0 mm² [6]. D'Arcangelo *et al.* reported a weld area of 9.94 mm² at 300–1000 W, corresponding to a width of 5.0–6.0 mm and a depth of 3.5–4.0 mm [7]. Compared with these studies, the blue laser welding process in the present study achieved comparable melting efficiency at a significantly lower power level, 600–760 W, with a weld cross-sectional area of approximately 8.8 mm², a width of 4.0–5.0 mm, and a depth of 2.5–3.5 mm. This directly reflects the advantage of the high energy absorption of copper at the 450 nm wavelength.

Compared with the infinity-shaped trajectory applied to aluminum alloy [21], which reduced the porosity ratio from 3.5% in conventional non-oscillating welding to below 1%, specifically 0.14–0.61% depending on scanning amplitude, and achieved a tensile strength of up to 93% of the base material, the Spiral–Elliptical trajectory in this study also showed no observable spatter or surface cracking under all 12 investigated conditions. Compared with the vision-recognition-based gap matching method for copper hairpins [6], which limited the assembly tolerance to a gap of 0–0.15 mm and a lateral displacement of 0–0.6 mm depending on the trajectory, the Spiral–Elliptical trajectory tolerated a gap of up to 569 μ m without requiring an auxiliary image recognition system. Regarding electromechanical performance, the “Good welding” group in [6] achieved a width of 4.28–4.37 mm, a resistance of 31–48 $\mu\Omega$, compared with 51 $\mu\Omega$ for the base material, and a tensile load of 387.74–710.9 N, compared with 1819.05 N for the base material. These values are of the same order of magnitude as those of samples A–D in the present study, which had widths of 4.39–4.62 mm, contact resistances of 30–60 $\mu\Omega$, and tensile loads of 323–450 N. This indicates that the Spiral–Elliptical trajectory achieves comparable electromechanical quality while tolerating a significantly larger assembly gap.

On this basis, the quality classification criteria were established as follows: based on width, a weld is considered acceptable when $4.0 \text{ mm} \leq \text{width} \leq 5.0 \text{ mm}$, insufficient when $\text{width} < 4.0 \text{ mm}$, and excessive when $\text{width} > 5.0 \text{ mm}$; based on depth, a weld is considered acceptable when $2.5 \text{ mm} \leq \text{depth} \leq 3.5 \text{ mm}$, insufficient when $\text{depth} < 2.5 \text{ mm}$, and excessive when $\text{depth} > 3.5 \text{ mm}$. Referring to Table 3, only the conditions at 680 W, namely Cases 5–8, simultaneously satisfied both criteria, establishing 680 W as the optimal process power within the investigated parameter range.

3.4. Tensile-shear test and contact resistance results

Four samples, A–D, corresponding to Cases 5–8, respectively, were used to validate the electromechanical performance of the welds within the optimal power window, as shown in Table 4. For comparison with boundary conditions, two excessive samples, E and F, welded at 760

W, and two insufficient samples, G and H, welded at 600 W, were also subjected to tensile-shear testing and contact resistance measurement. The results are presented together in Table 5, while the geometric data, including width and depth, of these samples remain limited to Table 3.

Table 4. Scanning parameters and geometric dimensions of samples A–D (680 W)

Sample	Spiral (mm/s)	Ellip. (mm/s)	Width (mm)	Depth (mm)
A	25	35	4.56	2.89
B	30	35	4.62	2.76
C	25	30	4.57	2.95
D	30	30	4.39	2.76

Table 5. Failure tensile load and contact resistance of samples A–H

Sample	Failure load (N)	Contact resistance ($\mu\Omega$)
A	450	60
B	445	48
C	372	38
D	323	30
E	420	5
F	387	7
G	278	165
H	193	204

The two excessive samples, E and F, achieved failure loads of 420 N and 387 N, with contact resistances of 5 $\mu\Omega$ and 7 $\mu\Omega$, respectively. The two insufficient samples, G and H, achieved failure loads of 278 N and 193 N, with contact resistances of 165 $\mu\Omega$ and 204 $\mu\Omega$, respectively. These results confirm the trend observed in samples A and B at 680 W: excessive welds exhibit very low contact resistance but involve potential risks due to over-penetration, whereas insufficient welds exhibit high contact resistance and low tensile strength, consistent with the classification in Table 3.

The slower scanning speed of the elliptical segment, 30 mm/s, prolonged the thermal interaction time in the central region, forming a thinner but more uniform metallurgical bond. This was favorable for electrical conduction but reduced the effective load-bearing bonding area. Conversely, the speed of 35 mm/s shortened the interaction time and could maintain a thicker molten zone through the thickness direction, which was beneficial for tensile strength but slightly increased the contact resistance. Therefore, the scanning speed of the elliptical segment acts as a control variable that enables an intentional balance between mechanical strength and electrical reliability within the same optimal power window. Overall, sample C, with a spiral speed of 25 mm/s and an elliptical speed of 30 mm/s, achieved the best balance, with a failure load of 372 N and a contact resistance of 38 $\mu\Omega$, both of which were at favorable levels compared with the other three samples. It is therefore proposed as the reference parameter combination for the blue laser welding process of copper hairpin wires using the Spiral–Elliptical trajectory at a laser power of 680 W.

4. Conclusions

This study experimentally investigated the blue laser welding process of Cu-ETP copper hairpin wires using a

combined Spiral–Elliptical scanning trajectory strategy, from which four main conclusions can be drawn.

First, within the power range of 600–760 W, penetration depth, rather than weld width, was the governing criterion for the process quality window. The weld width remained stable, at 4.3–4.9 mm, over the entire power range, whereas the penetration depth increased almost monotonically with laser power and both quality criteria (width 4.0–5.0 mm; depth 2.5–3.5 mm) were satisfied simultaneously only at 680 W.

Second, the Spiral–Elliptical trajectory exhibited good adaptability to practical assembly deviations, maintaining a fully fused joint even when the gap increased to 569 μm at high power.

Third, within the optimal power window of 680 W, the scanning speed of the elliptical segment governed a quantitative trade-off between tensile strength, 323–450 N, and contact resistance, 30–60 $\mu\Omega$, allowing the process parameters to be selected according to specific design priorities. The combination of a spiral speed of 25 mm/s and an elliptical speed of 30 mm/s, corresponding to sample C, achieved the best overall balance.

Fourth, compared with previously reported kilowatt-level infrared laser welding, blue laser welding using the Spiral–Elliptical trajectory achieved comparable weld geometric quality at a markedly lower power level, confirming the energy absorption advantage of the 450 nm wavelength for copper.

These results provide a quantitative experimental basis that can be directly applied to the selection and control of power and scanning-speed parameters in the industrial implementation of blue laser welding of copper hairpin wires. Future research may extend the experimental matrix to intermediate power levels around 680 W to refine the optimal window, incorporate microstructural and elemental composition analyses (e.g., SEM/EDS characterization of the weld interface [26]) to clarify the metallurgical mechanism underlying the strength–resistance trade-off, and combine thermal–fluid simulation with machine learning models to generalize the process window beyond the investigated data range.

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