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Long-term benchmarking of laser technologies and process improvement for Cu hairpin welding in electric drive manufacturing

-Invited Paper-

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Abstract

Remote laser welding is typically exploited for the joining of hairpin couples for the manufacturing of electric drives. Laser welding of copper hairpins poses several challenges due to the high optical reflectivity and elevated thermal conductivity of the material. Moreover, the welding operation is required to be clean, since it is carried out in a sub-assembly of the electric drive. The contemporary laser systems provide numerous possibilities for the welding process in terms of beam shapes and wavelengths. Hence, comparative analyses with well-defined criteria and protocols are required to assess the available technologies. Accordingly, this work illustrates the benchmarking of different laser welding systems in terms the mechanical strength and the process cleanliness during the welding Cu hairpins. Moreover, the monitoring approaches are described to ensure quality in a broad and distributed production environment. Additionally, mid-fidelity simulation is proposed to address the rapid selection between different beam solutions. The results of the presented framework presented are used to infer future beam configurations.

Keywords: Laser welding; Beam shaping; Green laser; Blue laser; E-mobility

1. Introduction

Electrification of vehicles is changing both the vehicle anatomy and the manufacturing technologies involved [1]. Moving to electric traction poses several challenges compared to the well-established manufacturing strategies employed for internal combustion engine vehicles. The electric drives used in the new generation vehicles are much simpler in form involving a drastic reduction in the number of components. On the other hand, newer materials such as FeSi alloys, Cu and polymeric insulators are used. The production of an internal combustion engine requires several sub-assemblies and assembly stages occasionally requiring manual labour depending on the vehicle segment and engine type. On the other hand, the electric drive can be manufactured in fully automated lines with some of the key components fed to the system in continuous bobbins such as the Cu bars [2]. Electrification along with increased usage of electronics is leading towards newer generation of models, preparing the stage towards autonomous vehicles.

The evolutionary perspective of vehicle technology requires the identification of sustainable, efficient and reliable manufacturing techniques. The electric drive is one of the key components in an electric vehicle. Contemporary lasers are

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considered as one of the key tools for the development of electric drives. Laser welding is the industrially accepted process to generate the connections between the free ends of the bent Cu bars positioned in the stator to generate the current flow path. The process involves the use of a laser beam to generate the permanent connection by fusion welding with no contact and in a remote fashion. The use of monitoring sensors stands out as a fundamental requirement for quality insurance considering the very high number of connections to be produced.

Laser technology has also been rapidly evolving. The currently available solutions span different wavelengths from the NIR to the visible range, figuring beam shaping capabilities and making use of integrated sensors [3]. The manufacturers of laser components are moving towards integrated solutions where source, beam steering elements and sensors are provided within preconfigured cells and adapted to production lines by system integrators. Moreover, the overall cost of laser systems is rapidly decaying and the possible beam configurations are increasing with an unprecedented pace. Hence, the difference between the available options is related to the process quality, robustness, and ease of use. The parallel expansion of product and process development generates a strong need for performance indicators. Due to the relatively recent development of these technologies, the standardization efforts for testing and benchmarking are still to be developed.

In the specific case of the joining of hairpins, laser welding encounters the well-known issues concerning high optical reflectivity and high thermal conductivity of the material. Scientific works have long investigated the process conditions leading to keyhole formation [4], porosity[5], and spattering [6] especially since the rise of solid-state fiber and disk sources in the early 2000s. The welding operation within the stator requires a high degree of process robustness and cleanliness. The welding process is carried out in a sub-assembly, where there are more than 200 connections per stator. The requirement for process capability index for stator production is stringent. Considering that the stator functioning relies on the single joints, the laser welding process is required to operate with very close to no defect conditions. Today's laser systems operate with multiple kW levels of power and high irradiance with shorter wavelengths at green and blue range ready to deliver improved quality for various applications. Benchmarking strategies need to be defined on the basis of the application needs enabling the testing of different solutions.

This work describes the benchmarking work carried out for Cu hairpin welding process using 8 different beam solutions tested over 3 years. The research underlines the main aspects of the testing procedures, the need for monitoring solutions to maintain quality as well as providing an outlook from the extracted data for the next generation laser systems.

2. Test standardization and process development

2.1. Material

The benchmark material was ETP1/OF1 quality 99.99% pure copper. The investigations were carried out with rectangular hairpin bars without electrical insulation with a width of 3.87 ±0.04 mm, a thickness of 2.66 ±0.03, and a corner radius of 0.67 ±0.03 mm.

2.2. Mechanical testing

The weld characterization can involve different measured entities including geometrical dimension, internal defects as well as electrical properties [7]. The mechanical properties of the welds have been found to be a critical point and correlated to the electrical performance [8]. Accordingly, the main standardized test was chosen for assessing the mechanical strength of the welds. Bare specimens of 65 mm length with flat ends were laser welded using the different laser solutions as seen in Fig.1.a.

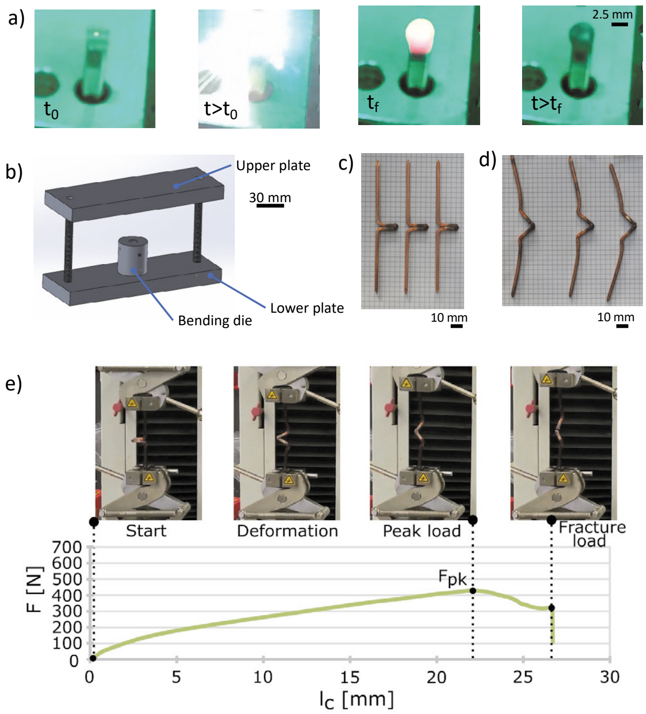

Fig. 1. Standardized testing of laser systems for hairpin welding. a) Laser welding, b) the bending die, c) pin couples after bending, d) pin couples after the mechanical testing, e) the different phases of the mechanical test.

Given the complex joint geometry, mechanical testing should be correctly chosen and adapted. Mechanical peel test based on BS EN ISO 14720:2016 has been adapted for the characterization of the weld strength [9]. The test may be employed to characterize the resistance of different pin sizes. The test involves the bending of the hairpin couples in order to allow for a suitable grip in universal testing machines. However, the bent shape and its dimensions are influential on the measured force at rupture. The welded specimens were thus bent to achieve specific dimension considering a flange length of 15 mm and a crosshead distance of 70 mm. A dedicated die was employed for the purpose (Fig.1.b) providing replicable results in terms of the specimen shapes before (Fig1.c) and after the mechanical testing (Fig 1.d). The test is carried out to identify the peak load to rupture, which is comparable with the bars of the same section size. Combined with the resistant section area determined on the fracture surface, it is possible to estimate mechanical strength.

2.3. Benchmarked systems

Over the period of 3 years of research the laser systems representing different technologies from NIR to visible range were tested. Representative welding conditions able to produce a sound bead with approximately 3 mm frontal bead height was sought at the highest productivity possible using elliptical trajectories. Table 1 reports the laser configurations along with the used process parameters. Fig. 2 shows example images of the beads produced.

Table 1. The laser systems and parameters investigated in the benchmarking work. *Power and beam levels referring to core/ring configurations.

Tag	λ (nm)	P (kW)	d_s (μm)	v (mm/s)	N
Hi NIR 85	1030	6	85	430	5
Hi NIR 150	1030	6	150	430	5
Hi NIR 340 BS	1070	2.1+3.9*	85/340*	300	6
Hi NIR 600 BS	1030	3+3*	150/600*	310	6
Hi NIR 156	1070	5	156	300	4
Mid NIR 215	1070	4	215	217	5
Mid Green 400	515	3	400	100	4
Mid Blue 720	455	3	720	100	5

As several laser systems were explored in the benchmarking work, different process parameters and optical configurations were used. Amongst the different comparative parameters, the cycle time (t_{cycle}) and the laser peak irradiance (I_0) are considered to be effective in establishing the main differences in terms of the process productivity and quality using the following expressions:

$$t_{cycle} = C \cdot N/v \quad (1)$$

$$I_0 = 8P/d_s^2\pi \quad (2)$$

where C is the circumference of the weld trajectory, which is adapted according to the beam size, N is the number of scans, v is the scan speed, P is the power, and d_s is the beam size defined with the $1/e^2$ method. The peak intensity for the ring/core configurations is calculated using the core power level and the size of the spot in the core region, while a more complete approach requires the fitting of the analytical description of the geometrical model on intensity profile measurements [10].

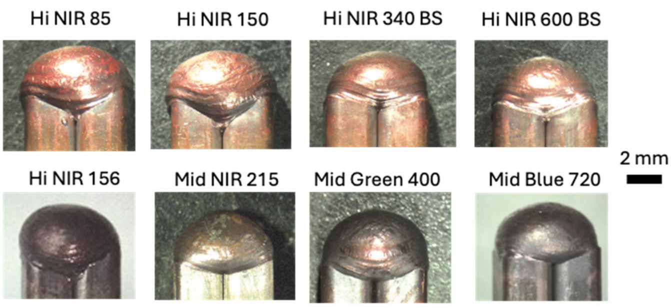

Fig. 2. Representative images of the beads produced with the benchmarked laser systems.

2.4. Weld strength and productivity

Fig. 3 reports the benchmarking results as a function of productivity (cycle time) and irradiance. It can be seen that the highest mechanical strength is achieved at the highest productivity condition with the highest intensity beam. The NIR laser sources all provide a keyhole mode weld. The weld duration is shortened as a function of the peak irradiance. The green laser source also provides a keyhole weld yet requiring longer processing time due to the relatively lower peak irradiance. The blue laser solution shows a similar behaviour although the process is mainly conduction based, which was observed through cross-section images not reported here for the sake of brevity. It should be noted that NIR lasers may fail to carry out the welding process at the same low peak irradiances of visible wavelength systems.

a)

b)

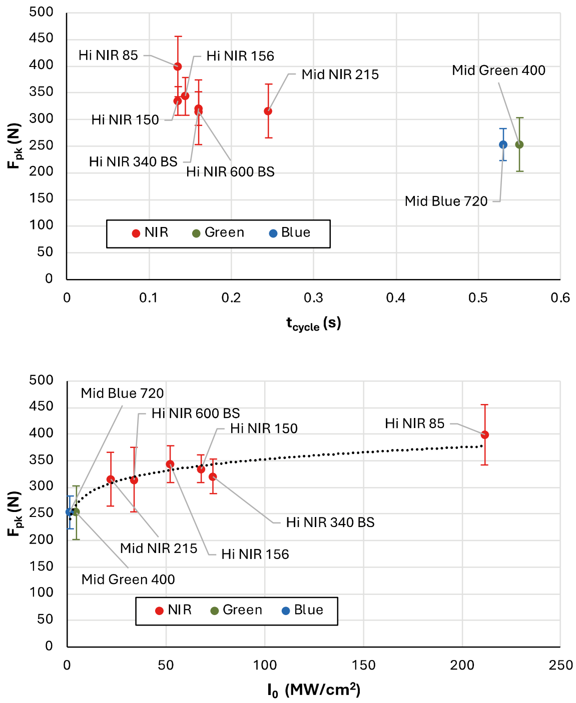

Fig. 3. Peak force to rupture F_{pk} as a function of (a) cycle time t_{cycle}, and (b) peak irradiance I_0. Dashed line is to depict trend only.

The benchmarking work provides insights to the impact of the welding process on the mechanical strength. In the particular form of the hairpin joints, the weld strength will be related to the size of the bead, internal defects, but also to the heat affected zone. The bead size is often a misleading parameter if measured via non-destructive methods. Indeed, internal defects such as pores reduce the effective contact area. Keyhole welds produce pores often entrapped at the bottom of the weld bead. While with high peak irradiance beams the risk of gas entrapment in a keyhole becomes more likely, these conditions also provide a wider contact area. The resultant effective contact area remains larger. The added benefit of a high irradiance beam also lies in the reduced processing time that also leads to a smaller heat affected zone. Pure Cu hairpins are produced from cold drawn bars with relatively higher rigidity thanks to the work hardening effect. The grain coarsening can start at temperatures as low as 300°C [11]. Heat penetration follows the interaction time roughly correlated by $\sqrt{t_{cycle}}$ [12]. The combined effects show that high intensity beams are beneficial for productivity and mechanical strength at the same time.

2.5. Weld cleanliness

Hairpin welds are carried out in an assembly stage where several components are exposed to the spatter and plume emissions from the process. Conversely to the productivity and strength, a keyhole process is more detrimental from the cleanliness perspective. Weld spatter is reduced through the use of conduction mode welding. The use of visible wavelength beams is essentially beneficial from this perspective as they can maintain the melting process with relatively low peak irradiance levels. Fig.4 illustrates the process emission in the case of a quasi-Gaussian beam shape and a core/ring configuration with 5 kW total power. The spatter ejection is evident at the early stages of the process with the Gaussian beam, where successful suppression of the droplet ejecta is achieved with the presence of a ring. The presence of the ring allows to stabilize melt flow around the keyhole opening and moving the process emission towards a plume dominant condition. The use of beam shaping evidently improves the process cleanliness as the removal of plume requires easier solutions compared to spatter droplets that can fly at much higher speeds.

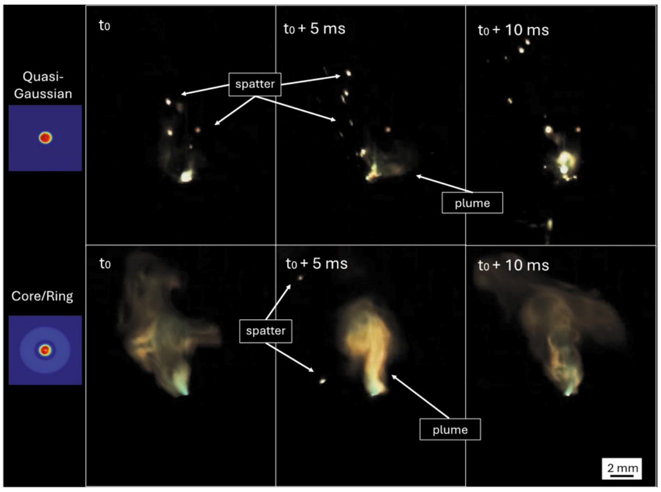

Fig. 4. Evolution of the process plume and spatter emission with a quasi-Gaussian beam (I_0=68 MW/cm^2) and a beam with added ring (I_0=20 MW/cm^2) at 5 kW total power.

3. Monitoring for quality insurance

3.1. Distributed network of process monitoring

The development of an effective process monitoring system often requires the specific choice of the sensors and the data analysis method for the given application. For the Cu hairpin welding, the sensor choice has been multiple coaxial photodiodes for ease of implementation over different types of laser source and process head combinations. The use of non-absolute measurement systems requires data acquisition to train statistical models. From this perspective, controlled experiments for supervised machine learning approaches are more accurate, while also laborious. The developed approach involves model training to be carried in-house to be later applied and further improved via the distributed network of machines from end-users (see Fig. 5).

The process monitoring has currently been developed for NIR lasers operating at 1 μm wavelength using the processing conditions of the Mid NIR 215 solution. In order to reduce the amount of experimental effort, 14 types of defects were determined beyond the reference welding condition. 20 welds were performed for the reference conditions whilst the defects were replicated 5 times, yielding a total of 90 welds as training dataset. Each weld was successively tagged for the defect type and its mechanical strength was also assessed through the standardized test.

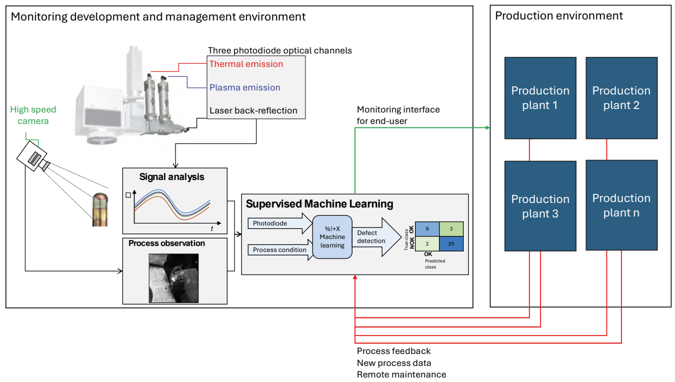

Fig. 5. The monitoring development and usage environments showing the information flow in stator manufacturing.

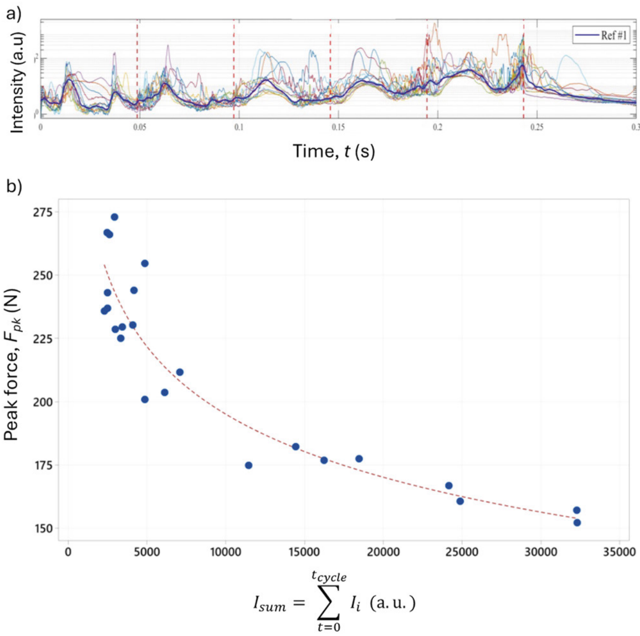

Fig. 6. a) Thermal channel signals acquired during the stable welding conditions using with a quasi-Gaussian beam (I_0=22 MW/cm^2) with 4 kW power (note the log scale in the intensity axis). b) Correlation of the total of the overall signal intensity against the mechanical strength.

3.2. Estimation of weld strength

The use of the monitoring approaches in laser welding requires sensor selection and feature engineering for specific defect types in the case of non-absolute measurement strategies

[13]. Photodiode signals are typically analysed by means of static acceptability bands generated via repeated experiments. Fig. 6.a shows a coaxial photodiode signal acquired from the thermal channel of the weld carried out using the Mid NIR 215 system. The blue line refers to an average reference signal, while the other lines correspond to several acquisitions carried out under stable conditions produced with I_0=22 MW/cm^2. It can be seen that the signal repeatability for forming an acceptability band is scarce.

One of the features that can be extracted is the total signal intensity in the thermal channel (I_{sum}) over the welding duration (t_{cycle}). The monitoring training set was used to establish the mechanical strength variation as seen in Fig 6.b. During the welding of hairpin couples with enamel, insufficient stripping of the insulation layer results in the loss of stable processing conditions producing excessive internal porosity. The process emission provides information related to the flame generated from the burning of the polymeric material. The increase in intensity may be observed in the thermal channel and the total signal intensity correlates to a decrease in the mechanical strength, thus providing an empirical estimation of the expected weld strength. The developed monitoring strategy also allows for physical interpretation which is highly desirable for industrial usage.

4. Digital process development

The simulation tools for laser welding are reaching a higher maturity. The digitalization of the process development is foreseen to be an important aspect to consider in long term benchmarking. Multi-physics models with fluid dynamic behaviour are reaching reasonable computation times that can be used for estimating initial process parameters as well as analysing the effects of different spatial beam profiles and different wavelengths. The main requirement for hairpin welding is the simulation of process transients also concerning the melt pool motion and solidification after the end of the joining process. The process benchmarking study revealed that the effective area of the molten material is a fundamental predictor for the strength of the joint. The spatter behaviour is required to be studied to ensure the process cleanliness. For industrial practice, the model accuracy does not necessarily need to provide an exact representation of the process. Model fidelity can be adjusted to provide comparative information between processing conditions.

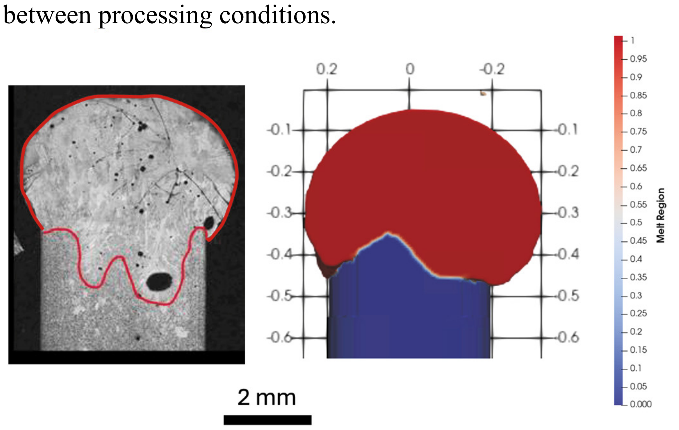

Fig. 7. Example of a mid-fidelity model result showing equivalent effective area sizes with 5 kW power at 200 mm/s and 3 scans.

A mid-fidelity simulation platform was tested using a commercially available software package (Flow3D Weld). The model incorporated computer fluid dynamics along with the thermal model for heating and cooling phases. The model was calibrated at this stage only for the NIR lasers with 1 µm wavelength with a temperature variable optical absorptivity profile adapted from Steen and Mazumder [12]. The multiple beam reflections and keyhole formation were included in the model, while pore formation was neglected. Fig.7 presents a comparison between a cross-section image of a welded Cu hairpin with the corresponding multi-physics simulation carried out with 5 kW laser power a beam waist diameter of 156 µm. The results show a general agreement for the bead shape while the exact keyhole profile and the pore entrapment are not fully represented by the simulation model. On the other hand, a sufficient match between the measured effective area could be observed. The measured bead effective area was 17.4 mm^2 with the simulated one at 18.4 mm^2 with an error margin of approximately 5%. With the proven suitability, the mid-fidelity approach can be further implemented with other wavelengths. A key point for further development is related to the optical absorptivity data.

5. Discussion

The long-term benchmarking work has shown that a global relationship across different laser sources can be established for what concerns the hairpin mechanical resistance. The mechanical strength of the connection is affected by the following main contributions:

- The connection area generated by the welding process. A larger area is required for higher mechanical strength.
- The internal voids, namely pores that reduce the effective resistant area. Pores can be generated both by the capillary instabilities in the keyhole as well as chemical affinity to the surrounding gases such as oxygen. Longer exposure of the melt pool to the surrounding atmosphere can generate more porosity.
- Heat affected zone beyond the weld seam generated due to the prolonged cycle times higher energy levels. The cold-drawn Cu hairpin wires are susceptible to grain coarsening consequently reducing the resistance.

The overall considerations indicate the need for a rapid weld process able to produce the required connection in a stable manner. The fastest processing condition corresponds to the highest intensity beam that also produces the strongest connection independently from the tested wavelengths. If the keyhole is generated, the dominant factor for the productivity remains the peak intensity of the beam. If the process is in a conduction dominant melting mode, the process is prolonged resulting in more energy released to the material. The conduction mode can provide an advantage for suppressing spatter and improving process cleanliness with the expense of a relatively lower mechanical properties.

The results show that a possible trade-off for improved productivity and quality resides in beam shapes adapted to the process needs. A high peak irradiance at low power levels can be achieved using single mode cores at NIR wavelength. The ring size and power content should be matched according to the wavelength. The use of visible wavelength beams can be exploited from this perspective as the total power requirement should be reduced. It should be noted that between green and blue wavelengths, the latter can provide higher wall-plug efficiency exploiting diode laser sources. However, to reach the required core/ring configurations at this wavelength, beam delivery solutions towards smaller beam sizes are still to be developed. The monitoring stage poses an important role for both productivity and quality. The overall production time should also consider the time to monitor and evaluate the data.

The physical benchmarking works require substantial amount of time and other resources. While the complete digitalization of the process development stage is not foreseen in the near future, the constant increase of the computational power is expected to reduce the simulation times drastically. Combined with the monitoring data, model calibration and validation stages can be further decreased. Future simulation efforts should also include the modelling of the sensor chain to assess the expected signal behaviour. Reverse solutions to identify the most suitable beam shapes for the application is another open point.

6. Conclusions

In this work, the methodology to assess several laser solutions for the welding of Cu hairpins has been illustrated. The work shows the necessity to identify a technical framework from process conception to quality insurance for the rapidly growing e-mobility field from the perspective of the given application. The work underlined that the highest productivity is achievable at the highest beam intensity. The NIR sources allow to reach high intensities and high-power levels. Visible wavelengths with relatively lower intensities may be beneficial for reducing spatter by a conduction mode weld. Ring profiles can be used to for the same purpose, but ideal beam profiles are still to be determined. From this perspective simulation models can be useful. Adjustment of the model fidelity can be considered to minimise the calculation times.

System reliability, service availability, footprint, energy efficiency, and usability are some of the other factors to be evaluated for a complete decision making. The technological maturity and economical scalability are bringing laser technology to the forefront of industrial production. The increase in the number of laser systems employed in the industry corresponds to new users. From this perspective the benchmarking efforts are expected to gain further relevance.

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