Effects of different laser welding parameters on the joint quality for dissimilar material joints for battery applications

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A B S T R A C T

For battery pack assemblies, it is crucial that the laser welded cell-to-busbar joints demonstrate both high mechanical strength and minimal electrical resistance. The present study investigates the effect of different laser welding parameters, on the mechanical strength, electrical resistance, porosity formation and joint microstructure, for dissimilar material cell-to-busbar joints. Laser welding experiments are performed, on thin nickel-plated copper and steel plates. The plates are joined in an overlap configuration, using laser beam wobbling and power modulation. Both circular and sinusoidal laser beam wobbling are used as selected strategies to increase the interface width of the joints, where also a comparison is made between the two methods. The joint quality is evaluated using joint geometry analysis, shear strength tests, computed tomography scanning and electrical resistance measurements. The results show that circular laser beam wobbling gives a larger joint shear strength compared with sinusoidal laser beam wobbling. In addition, it is observed that both the total pore volume and material mixing are significantly increased with increasing laser power and wobbling frequency for circular laser beam wobbling. However, for the sinusoidal laser beam wobbling the wobbling frequency does not show a significant impact on the total pore volume.

1. Introduction

The ongoing globally transition away from internal combustion engine vehicles towards electrified vehicles (EVs) brings new challenges for the automotive industries. The introduction of new technologies, development methods and fabrication methods for electrical machines, battery systems and power electronics are some typical examples of this. For high-performance EVs, high demands are placed on their battery systems, which must exhibit a high degree of reliability and durability, as well as high power densities, especially under severe driving conditions [1,2]. Hence, Lithium-ion (Li-ion) battery cells have increasingly come into focus for both researchers and manufacturers. This type of battery cells has a relatively low cost, good availability and high power density, which has resulted in an increased attention and use from EV battery system manufacturers [3]. Typically, EV battery systems are composed of many Li-ion cells, which are connected in series and/or in parallel, to form the battery modules. The battery modules are in the following interconnected to form complete battery packs. An individual battery pack often consist of several hundreds of individual Li-ion cells [4], which results in a large number of connection points that must be electrically and mechanically joined in a reliable way.

Current collectors, also called busbars, are frequently used as electrical conductors between individual cells and modules, and consist of thin plates made of an electrically conductive material, e.g. steel, copper (Cu), nickel (Ni) or aluminium (Al). To obtain a closed electrical circuit the busbars need to be connected to the positive/negative terminals of the cell by utilizing some joining technique, e.g. ultrasonic welding, resistance spot welding or laser welding [5–7]. Fig. 1 shows a schematic sketch of cylindrical Li-ion cells interconnected with busbars using laser-welded cell-to-busbar joints.

For cylindrical Li-ion cells, the battery casing and terminals are often made of Hilumin, which is an electro Ni-plated diffusion annealed steel strip obtaining both high corrosion resistance and low electrical resistance properties [2]. Furthermore, Ni-plated materials are frequently used for busbars as well, e.g. Ni-plated Cu plates [1]. This means that in order to connect cell terminals and busbars, several dissimilar materials must be joined. This must be done without obtaining a full penetration into the cell, and without an excessive heat impact on surrounding components and with a minimized generation of joint defects.

In research conducted by Sadeghian et al. [1] and Das et al. [4], the authors suggest that the main challenges for joining dissimilar materials...
are related to the differences in thermo-physical properties. Cracks, porosities or incomplete metallurgical bonds, are commonly seen joint defects caused by differences in thermal conductivity, thermal expansion coefficient or melting point [1]. Wallerstein et al. [8] provide a comprehensive review of the challenges involved during laser welding of aluminium to steel joints, emphasizing the considerable challenges arising from the differences in thermo-physical properties, as well as the limited solubility of the materials. Furthermore, in another review conducted by Kurytsev [9], the author highlight various methods for enhancing the joint quality for laser welded dissimilar material joints. Among the methods reviewed, the author suggests that laser beam wobbling can be used to increase the interaction area and to control the mixing of the two materials. In addition to this, the presence of intermetallic compounds (IMC) could result in decrease of both the electrical conductivity and the mechanical strength of dissimilar material joints [4]. Joint defects such as cracks, porosities or IMC could also lead to pitting and/or selective corrosion, which causes further degradation of the joint welded parts [10].

In summary, high quality dissimilar material joints in EV battery systems must exhibit the following characteristics: (1) good mechanical strength, (2) low electrical resistance, (3) low heat impact during joining and (4) high corrosion resistance. In order to fulfill such high requirements, an appropriate joining technique must be selected and the influence of process parameters on joint quality must be carefully studied.

Among the different welding technologies, e.g. arc welding, gas welding, resistance welding or electron beam welding, laser beam welding is an increasingly used joining technology that have shown excellent potential in producing cell-to-busbar joints [1]. Even for dissimilar materials, laser welding can obtain joints with high joint strength and low electrical resistance [1,2]. Moreover, laser beam welding is commonly used in several other EV applications as well, e.g. laser welding of battery casings or hairpin stators [4,11]. Compared to traditional welding methods, laser welding can offer a lower heat impact to the base material, a higher processing speed and is an promising technology for automation purposes. However, laser welding of dissimilar materials is still an challenging and understood task where further research is needed and ongoing, to fully understand and optimize the process and joint quality. For example in the work done by Yao et al. [12], the authors increased the joint tensile strength and reduced the amount of cracks and joint defects for laser welded Cu-steel butt joints by limiting the intermixing of the two welded parent materials. This was done by using a laser beam offset against the steel material. Similarly in the work done by Chen et al. [13], they showed that the micro crack formation and liquid separation could be avoided by reducing the intermixing of materials for laser welded Cu-stainless steel butt joints.

For Ni-plated Cu and steel plates, laser welded in an overlap configuration, the experimental studies done by Shaikh et al. [2] showed that the lap shear strength was positively correlated to the electrical resistance for the joints. Furthermore, this study showed that an individual increase in laser power, pulse-on-time or pulse frequency resulted in an increase of lap shear strength. Similar observations were made in the study conducted by Zapico et al. [14], were a correlation between the joint electrical resistance and the presence of hard and brittle phases was found for Ni-plated Cu and steel joints. The findings from this study shows that hard and brittle phases in the weld joint increases the electrical resistance of the joint.

Mehlmann et al. [3] used spatial power modulation (also referred to as laser beam wobbling, cf. [2]) in their research work to increase the cell-to-busbar contact area and to control the welding depth. They concluded that a favourable ratio between modulation amplitude and other laser parameters is needed in order to maximize the joint strength. The beam wobbling technique has been used by several authors in order to increase the contact area between cell terminal and busbar, as well as to keep the welding depth at a non-critical level. For example in the work done by Dimatto et al. [15], it was shown, for Al and Cu overlap joints, that the aspect ratio of the weld seam is dependent on the wobbling amplitude. An increased wobbling amplitude gave a wider and more shallow weld joint, which resulted in a reduced depth-to-width aspect ratio. Furthermore, the authors found that the mechanical strength of the joints increased with decreasing welding depth and also, that joints with high hardness values showed a high electrical resistance. In the experimental analysis performed by Asirvatham et al. [16], the authors found that the wobbling amplitude positively affects the mechanical strength and the electrical conductivity for thin steel to thick Al joints. This study also showed that larger wobbling amplitudes led to a lower mixing of Fe and Al in the joints, and thus a reduced formation of brittle IMC phases.

Another common technique for reducing the welding depth and heat impact for dissimilar material cell-to-busbar joints is to use pulsed laser welding [17], or to use pulsed laser welding in combination with beam wobbling [18]. Laser beam wobbling can also be used to reduce the porosity formation in weld joints. In [19], the amount of porosities in Al lap joints were significantly reduced by using circular beam wobbling together with high welding speeds.

Due to the varying absolute velocity of the laser spot in laser beam wobbling, and thus a spatially varying energy input, the welding depth varies along the produced weld seam. To reduce this effect, and simultaneously adjust the energy distribution, a power modulation technique can be used in combination with beam wobbling, as presented in the works done by Han et al. [20] and Hummel et al. [21]. In addition to compensating for a varying welding depth, Hummel et al. [21] showed that power modulation in combination with beam wobbling is a viable alternative to control cross section profiles. For the power modulation, the authors of this study used a compensation factor proportional to the difference in absolute velocity of the laser spot.

Until now, many authors have considered circular beam wobbling in their studies, e.g. [2,3,15,19,22,23], but research on other beam wobbling techniques are sparsely reported. One example could be sinusoidal beam wobbling, which can be considered for the same purpose as circular beam wobbling. However, only a very few comparisons between these two methods has been made, see for example [24,25]. Therefore, the aim of the present study is to investigate how circular and sinusoidal beam wobbling can be used for laser welding of dissimilar material cell-to-busbar joints, together with examining the differences between these two methods. Furthermore, a power modulation technique is used to reduce the variation in welding depth, for circular beam wobbling, following [21]. In the present study, a similar power modulation technique is used for sinusoidal beam wobbling, which until today, has not been widely explored.

To summarize, the scientific contributions of the present study are considered as:

![Fig. 1. Schematic sketch of cylindrical Li-ion cells interconnected with busbars using laser-welded cell-to-busbar joints.](image-url)
The Cu and Hilumin plates are joined in an overlap configuration using circular and sinusoidal laser beam wobbling. Furthermore, the joint quality is evaluated with larger thermal conductivity and reflectivity.

A comparison between circular and sinusoidal laser beam wobbling, with respect to joint quality

An investigation on the application of power modulation for sinusoidal laser beam wobbling

A proposal on how to join a thin steel plate, to a thicker Cu plate with larger thermal conductivity and reflectivity

An investigation of how different laser welding parameters affect the joint quality for dissimilar material cell-to-busbar joints

The remaining part of this paper is structured as follows. The materials used, and the experimental method are presented in Section 2. The experimental results obtained from the present study are presented in Section 3, followed by a discussion of the results in Section 4. Finally, the conclusions of the present study, together with suggestions for future work are given in Section 5.

2. Materials and experimental method

In the present study, the investigation is done by performing laser welding experiments on a simplified joint geometry, representing a cell-to-busbar joint in a Li-ion cell battery pack. Ni-plated Cu and Hilumin plates are joined in an overlap configuration using circular and sinusoidal laser beam wobbling. Furthermore, the joint quality is evaluated using joint geometry analysis, shear strength tests, computed tomography (CT) scanning, and temperature and electrical measurements of the joints. The influence of different laser welding parameters on the joint quality is presented by using response surface methodologies (RSM).

2.1. Materials

The selected specimens for this study is Ni-plated Cu and Hilumin plates with a thickness of 0.5 mm and 0.3 mm, respectively, a length of 100 mm and a width of 25 mm. The Cu plates are made of the material type Cu-PHC R240 with an electroplated Ni-layer with a nominal thickness of 1.5 μm. The Hilumin plates consist of DC04 steel with an electroplated Ni-layer with a nominal thickness of 2 μm. Table 1 lists the chemical composition for Cu-PHC R240 and DC04 steel.

The Cu and Hilumin plates are joined in an overlap configuration according to Fig. 2 with an overlap of 25 mm. The weld seam is 15 mm long and created by the utilization of laser beam wobbling.

\[ x(t) = \frac{a_w}{2} \cos \left( 2\pi f_w t + \phi \right) + v_x t \]

\[ y(t) = \frac{a_w}{2} \sin \left( 2\pi f_w t + \phi \right) \]

(1)

The laser welding experiments are carried out using a Trumpf Tru-Laser Cell 3000 5-axis laser machine, equipped with a programmable focusing optics (PFO) of the type PFO 33-2. The PFO is used for laser beam delivery and realization of laser beam wobbling. The laser source is a Trumpf TruDisk 6001 solid-state disk laser. The generated laser light is delivered to the focusing optics through a 2-in-1 fibre, i.e. core and ring fibre. Further details about the laser source and the optics configuration are presented in Table 2.

2.2. Laser welding experiments

As shown in Fig. 3, the specimens are clamped together using a customized fixture in order to reduce the part-to-part gap. To prevent heat transfer between specimens and fixture, all contact surfaces are insulated with bakelite. All specimens are cleaned with 2-propanol before the experiments. In order to eliminate any back reflections of laser light into the optics, the laser welding is performed with a 25 mm offset between focusing optics and joint position. This results in a laser beam inclination angle of approximately 3°, see Fig. 3.

In the experiments, weld seams are produced for different laser output powers, \( P \), using both circular and sinusoidal beam wobbling. Here, the laser path consists of a linear feed rate, \( v_x \), with a superimposed circular or transverse oscillating motion, according to Fig. 4. This oscillating motion is characterized by the wobbling frequency, \( f_w \), and the wobbling amplitude, \( a_w \).

The laser path for a clockwise circular wobbling pattern is described by the corresponding \( x \) - and \( y \)-coordinates according to

<table>
<thead>
<tr>
<th>Table 1 Chemical composition for the considered materials (wt.%).</th>
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<tbody>
<tr>
<td>Cu-PHC</td>
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<tr>
<td>DC04</td>
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</table>

<table>
<thead>
<tr>
<th>Table 2 Laser source and optics configuration.</th>
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</thead>
<tbody>
<tr>
<td>Adjustable power [W]</td>
</tr>
<tr>
<td>Wavelength [mm]</td>
</tr>
<tr>
<td>Fibre core diameter [μm]</td>
</tr>
<tr>
<td>Fibre ring diameter [μm]</td>
</tr>
<tr>
<td>Focal length [mm]</td>
</tr>
<tr>
<td>Collimation length [mm]</td>
</tr>
<tr>
<td>Aspect ratio [-]</td>
</tr>
<tr>
<td>Focal spot diameter [μm]</td>
</tr>
<tr>
<td>Beam parameter product [mm mrad]</td>
</tr>
<tr>
<td>Field size PFO [mm²]</td>
</tr>
</tbody>
</table>
where $t$ is the processing time. The tangential velocity for the circular motion, $v_{tx}$, can be described by

$$v_{tx} = \frac{a_w}{2} 2\pi f_w = \pi a_w f_w$$  \hspace{1cm} (2)

The sinusoidal wobbling pattern is described in a similar way with corresponding $x$- and $y$-coordinates according to

$$x_s(t) = v_f t$$

$$y_s(t) = \frac{a_w}{2} \sin \left( 2\pi f_w t \right)$$ \hspace{1cm} (3)

The tangential velocity for the transverse motion is described by the time derivative of the $y$-coordinate, according to

$$v_{ty} = \frac{dy_s}{dt} = \pi a_w f_w \cos \left( 2\pi f_w t \right)$$ \hspace{1cm} (4)

The corresponding absolute velocities, i.e., the speed of the laser spot, are for both the circular and sinusoidal wobbling patterns given by

$$v_{abs} = \sqrt{ \left( \frac{dx}{dt} \right)^2 + \left( \frac{dy}{dt} \right)^2 }$$ \hspace{1cm} (5)

where $\frac{dx}{dt}$ and $\frac{dy}{dt}$ corresponds to the time derivatives of Eqs. (1) and (3), where the indices $i = [c,s]$ stands for circular and sinusoidal wobbling, respectively. The distance $d$ in Fig. 4, is the travelled distance in the feed ($x$) direction during one oscillation, i.e. the distance for one wobbling period. This distance is given by

$$d = \frac{v_f}{f_w}$$ \hspace{1cm} (6)

for both circular and sinusoidal beam wobbling.

The specimens are welded using varied $P$, $v_f$, and $f_w$, in order to investigate how these parameter changes will affect the joint quality. The wobbling amplitude, $a_w$, and the defocusing, are kept constant at 0.5 mm and 0 mm, respectively. Furthermore, a constant power modulation scheme, according to Fig. 5, is used in order to reduce the energy input at points with low absolute velocity, i.e., points where the transverse velocity is zero, or points where the tangential velocity is in the opposite direction to $v_f$, for the circular and sinusoidal wobbling patterns, respectively. In Fig. 5, the percentage of the peak power is plotted against the wobbling angle for one oscillation for both the circular and sinusoidal wobbling patterns. Here, the change in peak power is proportional to the change in absolute velocity of the laser spot due to the wobbling pattern, similar to the approach used in [21]. Since the absolute velocity does not vary equally for circular and sinusoidal beam wobbling, the power is modulated differently for the different cases. This means that the average power differs slightly between circular and sinusoidal beam wobbling (67.5% of peak power for circular beam wobbling and 62.5% for sinusoidal beam wobbling), which leads to a difference in energy output of 8% for the different cases.

In this study Design of Experiments (DoE) is utilized, in order to carry out a systematic investigation and simultaneously reduce the number of trials. Based on the literature review and our previous knowledge, $P$, $v_f$, and $f_w$ are selected as the independent variables. Furthermore, the joint quality, in terms of in-process temperatures, weld joint geometry, joint shear strength, electrical resistance and total pore volume, are considered as the dependent variables. The sampling points are determined using a 3-level 3-factor Box–Behnken experimental design where the boundaries are identified from initial welding trials for parameter screening. In these initial trials, welds are performed with varied output power for different feed rate and frequency levels. Furthermore, a constant amplitude of $a_w = 0.5$ mm and power modulation according to Fig. 5, are used for both circular and sinusoidal beam wobbling. For a linear feed rate below $v_f = 90$ mm/s, it is found that the welding depth and weld seam width increases in the feed rate direction, due to a larger influence of thermal conduction. Therefore, this feed rate is seen as the lowest possible. The distance for one wobbling period, $d$, determines whether the wobbling pattern is compressed or stretched. This distance also provides potential limits for maximum and minimum values of frequency and feed rate, following Eq. (6). The upper frequency boundary of 249 Hz, is determined by machine limitations. During the initial trials, the welds are defined as underwelded if there appear traces of burn mark on the underside of the plates. Plates with lack of joining are seen as overwelded. With this in mind, it is found that a power range of 1950–2070 W can be used for feed rates between 120–140 mm/s and frequencies between 211–249 Hz. This corresponds to a wobbling distance $d$, between 0.48–0.66 mm.

The experimental design with corresponding sampling points are presented in Fig. 6 and Table 3. The centre point in this Box–Behnken design is repeated three times, corresponding to sampling points 13–15 for the circular beam wobbling and points 28–30 for the sinusoidal beam wobbling. Each sampling point for the experimental design in Table 3 is repeated four times, for both circular and sinusoidal beam wobbling, where three repeated sample sets are used for temperature/resistance measurements and shear strength testing and one sample set for porosity and joint geometry analysis. In order to avoid bias effects, the order of execution for the sampling points is randomized during the experiments. Furthermore, Table 3 shows the normalized values of power, linear feed rate and wobbling frequency, $P'$, $v_f'$ and $f_w'$, which are used for the fitting of linear regression models.
Table 3
Experimental sampling points (#-column represents the sampling point numbers, where the first number corresponds to circular beam wobbling and numbers in parenthesis corresponds to sinusoidal beam wobbling).

<table>
<thead>
<tr>
<th>#</th>
<th>[W]</th>
<th>[mm/s]</th>
<th>[Hz]</th>
<th>[–]</th>
<th>[–]</th>
<th>[–]</th>
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<tbody>
<tr>
<td>1 (16)</td>
<td>1950</td>
<td>120</td>
<td>230</td>
<td>0</td>
<td>0</td>
<td>0.5</td>
</tr>
<tr>
<td>2 (17)</td>
<td>1950</td>
<td>140</td>
<td>230</td>
<td>0</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>3 (18)</td>
<td>2070</td>
<td>120</td>
<td>230</td>
<td>1</td>
<td>0</td>
<td>0.5</td>
</tr>
<tr>
<td>4 (19)</td>
<td>2070</td>
<td>140</td>
<td>230</td>
<td>1</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>5 (20)</td>
<td>1950</td>
<td>130</td>
<td>211</td>
<td>0</td>
<td>0.5</td>
<td>0</td>
</tr>
<tr>
<td>6 (21)</td>
<td>1950</td>
<td>130</td>
<td>249</td>
<td>0</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>7 (22)</td>
<td>2070</td>
<td>130</td>
<td>211</td>
<td>1</td>
<td>0.5</td>
<td>0</td>
</tr>
<tr>
<td>8 (23)</td>
<td>2070</td>
<td>130</td>
<td>249</td>
<td>1</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>9 (24)</td>
<td>2010</td>
<td>120</td>
<td>211</td>
<td>0.5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>10 (25)</td>
<td>2010</td>
<td>120</td>
<td>249</td>
<td>0.5</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>11 (26)</td>
<td>2010</td>
<td>140</td>
<td>211</td>
<td>0.5</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>12 (27)</td>
<td>2010</td>
<td>140</td>
<td>249</td>
<td>0.5</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>13 (28)</td>
<td>2010</td>
<td>130</td>
<td>230</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>14 (29)</td>
<td>2010</td>
<td>130</td>
<td>230</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>15 (30)</td>
<td>2010</td>
<td>130</td>
<td>230</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
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2.3. Measurement of in-process temperatures

In order to investigate how different process parameters affect the in-process temperatures during welding, temperature measurements are conducted for all experiments. Thermo-couples (TCs) of type K and cross sectional area 0.051 mm$^2$ (AWG 30) are mounted on the underside of the specimen, directly below the weld joint, in order to measure the resulting in-process temperature during welding. The TC voltage signal is amplified and acquired using a Phoenix contact signal amplifier of the type MINI MCR-2-TC-UI and a National Instruments USB 6210 data acquisition card together with the data acquisition tool box in MATLAB. Furthermore, to investigate how the melt pool behaviour and spatter is affected by different process parameters and welding patterns, high-speed videos are captured for each experiment using a Photron FASTCAM NOVA S9 high-speed camera with a frame rate of 9000 fps and a resolution of 1024 $\times$ 1024 pixels. The location of the thermocouples and the high-speed camera, in the experimental set-up are shown in Fig. 3. A high-speed video from the experiment for sampling point 13 is included as Supplementary Content to this article. This video shows an example of melt pool behaviour and spatter formation during circular laser beam wobbling.

2.4. Joint geometry analysis

To examine the weld joint geometry micrographs of the welded specimens are prepared. The specimens are cut across the weld seam, both normal and longitudinal to the feed rate direction, in the centre of the weld seam. Micrographs of cross sections in the longitudinal direction are used to investigate the welding depth variation due to the wobbling motion and to verify the welding depth measured from normal cross sections. After cutting, the specimens are mounted in resin, ground, polished and etched, then investigated using an optical microscope (Zeiss Stemi 2000-C).

A schematic sketch of cross sections in the normal and longitudinal directions are presented in Fig. 7a and Fig. 7b, respectively. Here, $w_t$ and $w_i$ are the width of the weld seam, measured at the top surface of the copper plate and at the copper–steel interface, respectively. The distance $d_p$ is the maximum welding depth in the steel plate.

2.5. Shear strength tests

In the following, the mechanical strength of the joints is evaluated in terms of shear strength tests performed in an Instron 8872 tensile test machine equipped with an 30 kN calibrated load cell. The joint geometry, as well as the utilized testing method follows [2,26], which have similarities to the tests conducted in [17–19,27]. The welded specimens are clamped in the machine grips using shim sheets of thickness 0.3 mm and 0.5 mm against the copper and Hilumin side, respectively, in order to obtain a coaxial loading. For a constant displacement rate of 0.5 mm/min the specimens are loaded until complete failure. Three repetitions are performed for each sampling point, for which the maximum loads are extracted from the load–displacement curves. For each specimen the fracture mode and the corresponding fracture surface are evaluated.

2.6. Measurement of electrical resistance and temperature rise

The electrical resistance of the weld joints is evaluated using a four point measurement method. This is a commonly used method to measure the resistance of dissimilar material joints, cf. [27,28]. Fig. 8 shows a schematic sketch of the measurement setup, where the voltages $U_{Cu}$, $U_{joint}$ and $U_{Hil}$ are measured. The voltages are measured along a length $L_{Cu}$ for the Cu plate, overlap joint, and Hilumin plate when a direct current $I$ is led through the specimen. The resistances for this measuring length can be directly derived from Ohm’s law, according to

$$U_i = R_i I$$  \hspace{0.5cm} (7)
for both base material and joint. In order to compare the electrical resistance between joint and base material, the resistance k-factor is used, which for dissimilar material joints is given by [28]

\[ k = \frac{2U_{\text{joint}}}{U_{\text{Cu}} + U_{\text{Hi}}} = \frac{2R_{\text{joint}}}{R_{\text{Cu}} + R_{\text{Hi}}} \]  

(8)

A value of \( k = 1 \) means that the joint resistance is equal to the electrical resistance of the base material and a value of \( k > 1 \) means that the joint resistance is larger compared with the base material. The measurements are performed in room temperature for a direct current of \( I = 15 \, \text{A} \) and a measuring length \( L = 40 \, \text{mm} \). The current is supplied using a HP 6675 A DC power supply and the voltage is measured using a HP 34401 A multimeter. In addition, the temperature rise in the weld joints, due to the supplied current, is measured using a thermal camera of the type thermoIMAGER TIM 230 from MICRO-EPSILON. The thermal camera is aimed at the top surface of the specimen and continuously measures the temperature field in a 25 mm \( \times \) 25 mm area centred over the weld joint.

2.7. Porosity analysis

To evaluate the amount of porosity in the weld joints, the specimens are CT-scanned using an EasyTom 3D CT system from RX-solutions. After the data acquisition, the X-ray images are reconstructed into 3D volumes using the CT reconstruction software Xact. For each 3D volume, the amount of porosity is calculated in terms of total pore volume using the CT analysis software VG studio max.

3. Results

In this section, we present an analysis of the resultant joint quality, concerning in-process temperatures, weld joint geometry, joint shear strength, electrical resistance, and porosity levels, with respect to process parameters. Furthermore, the experimentally measured quality measures are fitted to linear regression models using a step-wise regression method. The independent variables, i.e. the welding parameters, are normalized to the range \([0, 1]\) prior to the fit, see Table 3. The accuracy for the regression models are evaluated in terms of \( R^2 \) and RMSE values.

The produced weld joints are classified as underwelded if the plates have received a lack of joining, sufficiently welded if the plates are joined and the lower plate is not fully penetrated, or overwelded if there are visible traces of burn mark on the lower plate. Typical appearances of sufficiently welded and overwelded joints, for the circular beam wobbling, are shown in Fig. 9. None of the samples 1–30 are observed as underwelded and Table 4 shows whether the samples are classified as sufficiently welded or overwelded. For some of the samples, only a small change in the surface of the underside of the specimens was observed, which corresponds to a full penetration in only one or two points, i.e. in the beginning or end of the weld seam. These samples are classified as sufficiently welded but are marked with an asterisk (*) in Table 4.

3.1. Resulting in-process temperatures

From the acquired temperature signals the maximum in-process temperatures are noted. These, experimentally measured maximum temperatures, with respect to the normalized laser output power, \( P' \) and the normalized linear feed rate, \( v'_L \), are plotted for constant frequency values \( f_w = [211, 230, 249] \, \text{Hz} \). This is seen, for circular and sinusoidal beam wobbling in Fig. 10a and 10b, respectively. The experimentally measured maximum temperatures are fitted to linear regression models where the resulting equations are shown in Fig. 10 and the corresponding model coefficients are shown in Table 5. The resulting values of \( R^2 \) and RMSE are 0.312 and 42.1 °C for the circular model, and the corresponding values for the sinusoidal model are 0.497 and 35.0 °C, respectively.

The experimental results for the circular beam wobbling in Fig. 10a shows that the in-process temperature is generally increased with increasing power and decreasing feed rate. A barely noticeable effect is seen on the in-process temperature due to changes in wobbling frequency. However, for the sinusoidal beam wobbling the in-process temperature is significantly affected by changes in wobbling frequency. Referring to Fig. 10b, one can observe that the temperature increases with decreasing feed rate for a frequency of 211 Hz, but for frequencies of 230 Hz and 249 Hz the temperature only increases to a certain value and then decreases as the feed rate is decreased. A possible explanation for this is when the wobbling frequency is increased the wobbling pattern will get more compressed, that are observed to increase the risk of burning through the lower plate. When the lower plate is burned through the keyhole collapses, allowing melt and vapour to escape from the workpiece, which may lead to a lower in-process temperature. This could explain that the temperature increases with decreasing feed rate until the lower plate is burned through, then the temperature decreases with increasing feed rate due to a larger extent of burn through. The minimum observed in-process temperatures for circular and sinusoidal beam wobbling are 53 °C and 51 °C, respectively.

3.2. Weld joint geometry and joint microstructure

Fig. 11a–c shows typical micrographs from cross sections in the normal direction for the circular beam wobbling. In addition, this figure
Fig. 10. Maximum in-process temperatures for circular (a) and sinusoidal (b) beam wobbling. The black circles represent experimentally measured values and the coloured surface represents a linear regression model fitted to the data, which is described by the corresponding equation.

![Temperature plots for circular (a) and sinusoidal (b) beam wobbling.](image_url)

Fig. 11. Micrographs from cross sections in normal (a–c) and longitudinal (d–f) direction of weld joints produced using circular beam wobbling corresponding to sampling points 6 (a, d), 15 (b, e) and 7 (c, f).

![Micrographs of weld joints.](image_url)

Table 5
Linear regression coefficients for in-process temperatures for circular and sinusoidal beam wobbling.

<table>
<thead>
<tr>
<th></th>
<th>$t_{c1}$</th>
<th>$t_{c2}$</th>
<th>$t_{c3}$</th>
<th>$t_{c4}$</th>
<th>$t_{c5}$</th>
<th>$t_{c6}$</th>
<th>$t_{c7}$</th>
<th>$t_{c8}$</th>
<th>$t_{c9}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circular</td>
<td>121</td>
<td>89.7</td>
<td>-70.1</td>
<td>-55.5</td>
<td>220</td>
<td>77.7</td>
<td>-50.7</td>
<td>45.3</td>
<td>-264</td>
</tr>
<tr>
<td>Sinusoidal</td>
<td>184</td>
<td>33.4</td>
<td>-254</td>
<td>-303</td>
<td>645</td>
<td>155</td>
<td>210</td>
<td>-414</td>
<td>-156</td>
</tr>
</tbody>
</table>

Fig. 12 a–c and Fig. 12 d–f illustrates representative micrographs of sinusoidal beam wobbling, captured from cross sections along the normal and longitudinal directions, respectively. The micrographs in Fig. 12 a–c represent weld joints corresponding to sampling points 25, 30 and 26 for which the power has been kept constant at $P = 2010$ W and where the feed rate and wobbling frequency have been varied. As seen in Fig. 12 d–f, for the sinusoidal beam wobbling, the welding depth decreases with increased feed rate and decreased wobbling frequency. This can be explained by the lower energy input associated with a higher feed rate, as well as the more extended wobbling pattern associated with a lower wobbling frequency.

It is worth noticing, that the welding depth varies in the longitudinal direction, even though power modulation has been used. Consequently, it is difficult to verify that the cross sections in the normal direction has been made at the maximum welding depth, c.f. Fig. 11 a–c and Fig. 12 a–c. Therefore, the maximum welding depth, measured from the longitudinal cross sections, is used as quality measure of the joints for the further analysis.

Fig. 13a and Fig. 13b, shows the experimentally measured welding depth with respect to the normalized laser output power, $P'$, and the normalized linear feed rate, $v_f'$. For constant frequency values $f_w = [211, 230, 249]$ Hz, for circular and sinusoidal beam wobbling,
respectively. Moreover, linear regression models are fitted to the experimentally measured welding depth, where the resulting equations and the corresponding model coefficients are shown in Fig. 13 and Table 6, respectively. The resulting values of $R^2$ and RMSE are 0.937 and 0.0202 mm for the circular model, and the corresponding values for the sinusoidal model are 0.993 and 0.0066 mm, respectively.

For circular beam wobbling, it can be seen from Fig. 13a that the welding depth generally increases with increased power, and for high powers and low feed rates the welding depth also increases with decreased wobbling frequency. For the low and mid wobbling frequencies (211 Hz and 230 Hz), the welding depth generally increases with decreasing feed rate, except for the lowest power. But for the high wobbling frequency (249 Hz) the opposite behaviour is observed.

For sinusoidal beam wobbling, Fig. 13b shows that the welding depth generally increases with increasing power and decreasing feed rate. But for the high wobbling frequency (249 Hz) the welding depth increases with increasing power up to a power level around 2010 W, then the welding depth decreases with increasing power. However, it is only one measurement that produces this behaviour.

Similarly to the welding depth, the experimentally measured interfacce width is shown together with a linear regression model fitted to experimental values in Fig. 14a and Fig. 14b, corresponding to circular and sinusoidal beam wobbling, respectively. Here, the interface width is plotted with respect to the normalized laser output power, $P'$, and the normalized linear feed rate, $v'_f$, for constant frequency values. For the linear regression model the resulting equations and the corresponding model coefficients are shown in Fig. 14 and Table 7, respectively. Corresponding $R^2$ and RMSE values are 0.647 and 0.0745 mm for the circular model, and 0.561 and 0.048 mm for the sinusoidal model.

From Fig. 14a-b it can be seen that the interface width increases with increasing power and decreasing feed rate, both for circular and sinusoidal beam wobbling, respectively. Here, the interface width is plotted with respect to the normalized laser output power, $P'$, and the normalized linear feed rate, $v'_f$, for constant frequency values. For the linear regression model the resulting equations and the corresponding model coefficients are shown in Fig. 14 and Table 7, respectively. Corresponding $R^2$ and RMSE values are 0.647 and 0.0745 mm for the circular model, and 0.561 and 0.048 mm for the sinusoidal model.

From Fig. 14a-b it can be seen that the interface width increases with increasing power and decreasing feed rate, both for circular and sinusoidal beam wobbling, respectively.
lar and sinusoidal beam wobbling. For the sinusoidal beam wobbling increases with decreasing feed rate and increasing power for both circular and sinusoidal beam wobbling. The maximum observed joint shear strengths for circular and sinusoidal beam wobbling are 1601 N and 1253 N, respectively. These observations correspond to sampling points 10 and 22 with welding parameters according to Table 3.

### 3.3. Joint shear strength

For each sampling point, the maximum shear load is extracted from the corresponding load–displacement curve, which is further considered as the joint shear strength for each sample. Fig. 15 shows the load–displacement curves for three repetitions of sampling points 15 and 30, corresponding to the centre point of the experimental design for circular and sinusoidal beam wobbling, respectively.

It is clear that the joint shear strength decreases with an increase in wobbling frequency, but for the circular beam wobbling the behaviour is reversed, albeit not as clearly, c.f. Fig. 16a and Fig. 16b. For the circular beam wobbling, it appears that the shear strength, at low feed rates and high powers, converges towards a maximum as the frequency increases. Fig. 17 shows the joint shear strength plotted versus the wobbling frequency for a constant feed rate of \(v_f' = 130 \text{ mm/s}\) and power values of \(P = [1950, 2010, 2070] \text{ W}\) for both circular and sinusoidal beam wobbling. Here it is clearly shown that the joint shear strength is increased with an increasing wobbling frequency for circular beam wobbling but decreased for sinusoidal beam wobbling. Furthermore, it can be seen that the effect of the frequency on the shear strength decreases with increasing power for the circular beam wobbling. The maximum observed joint shear strengths for circular and sinusoidal beam wobbling are 1601 N and 1253 N, respectively. These observations correspond to sampling points 10 and 22 with welding parameters according to Table 3.

### 3.4. Electrical resistance and temperature rise

The resistance k-factor is evaluated from measured voltage drops for each sampling point. In Fig. 18a and Fig. 18b, the measured k-factor values are plotted with respect to the normalized laser output power, \(P'\), and the normalized linear feed rate, \(v_f'/v_{f,c}\), for constant frequency values.

### Table 7

<table>
<thead>
<tr>
<th>Linear regression coefficients for interface width for circular and sinusoidal beam wobbling.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(w_1)</td>
</tr>
<tr>
<td>Circular</td>
</tr>
<tr>
<td>Sinusoidal</td>
</tr>
</tbody>
</table>

Fig. 14. Interface width for circular (a) and sinusoidal (b) beam wobbling. The black circles represent experimentally measured values and the coloured surface represents a linear regression model fitted to the data, which is described by the corresponding equation.

Fig. 15. Load–displacement curves for three repetitions of sampling points 15 and 30, corresponding to the centre point of the experimental design for circular and sinusoidal beam wobbling, respectively.

The resistance k-factor is evaluated from measured voltage drops for each sampling point. In Fig. 18a and Fig. 18b, the measured k-factor values are plotted with respect to the normalized laser output power, \(P'\), and the normalized linear feed rate, \(v_f'/v_{f,c}\), for constant frequency values.
On closer examination of Fig. 18a, it can be seen that the resistance k-factor decreases with increasing power and decreasing feed rate for the circular beam wobbling. However, this effect decreases with increasing frequency. For a constant frequency of $f = 249$ Hz ($f'_w = 1$), the resistance k-factor does not vary significantly with respect to power and feed rate.

The resistance k-factor for the sinusoidal beam wobbling, as shown in Fig. 18b, exhibits a slightly different behaviour compared to the circular beam wobbling. For low power values the resistance k-factor decreases with decreasing feed rate, but when the power is increased there is a shift in behaviour. For high power values the resistance k-factor are instead increasing with decreasing feed rate. For the sinusoidal beam wobbling it can also be seen that the resistance k-factor increases slightly with an increased frequency, contrary to the circular beam wobbling, where the k-factor, to some extent, decreases with increasing frequency.

The minimum observed resistance k-factor values, for circular and sinusoidal beam wobbling, are 1.026 and 1.04, respectively. These observations correspond to sampling points 7 and 19 with welding parameters according to Table 3. During the electrical measurements, no significant temperature increase was measured in the samples.

### 3.5. Amount of porosity in joints

For each sampling point, the total pore volume is extracted from the corresponding 3D volume, reconstructed from X-ray images. Fig. 19a–c shows longitudinal CT slices in the middle of the weld seam for sampling points 5 (a), 14 (b) and 8 (c), corresponding to samples produced using circular beam wobbling with a constant feed rate of $v_f = 130$ mm/s and varied laser output power and wobbling frequency according to Fig. 6 and Table 3. The coloured areas in Fig. 19 visualize observed porosities where the colour scale represents individual pore volume. These results clearly show that, the amount of porosity in the weld joints is significantly increased with increasing power and wobbling frequency. The bright areas in the CT slices in Fig. 19 represent areas with a difference in density compared to the base material, which can be explained by the fact that copper and steel have been mixed during the welding process. By examining Fig. 19a–c, it can be seen that the material mixing increases with increasing power and frequency.

In Fig. 20a and Fig. 20b, the total pore volume is plotted with respect to the normalized laser output power, $P'$ and the normalized linear feed rate, $v'_f$, for constant frequency values, for circular and sinusoidal beam wobbling, respectively. Furthermore, the total pore volume, measured from CT-data, is fitted to linear regression models where the resulting equations and the corresponding model coefficients are shown in Fig. 20 and Table 9, respectively. The resulting values of $R^2$ and RMSE are 0.982 and 0.0172 mm$^3$ for the circular model, and the corresponding values for the sinusoidal model are 0.958 and 0.0172 mm$^3$, respectively.

For circular beam wobbling, it is evident from Fig. 20a, that the total pore volume increases with increasing laser output power and wobbling frequency. The relationship between feed rate and total pore volume is not as clear, however, it can be seen that at low wobbling frequency the total pore volume increases with decreasing feed rate, but for high wobbling frequency the pore volume instead decreases with decreasing feed rate. Worth to notice is that the regression model predicts negative pore volumes at low power and high feed rate for the lowest frequency for circular beam wobbling, these negative values should be considered as pore volumes close to zero.

### Table 8

<table>
<thead>
<tr>
<th>Linear regression coefficients for joint shear strength for circular and sinusoidal beam wobbling.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circular</td>
</tr>
<tr>
<td>Circular</td>
</tr>
<tr>
<td>Sinusoidal</td>
</tr>
</tbody>
</table>

For circular and sinusoidal beam wobbling, respectively. In addition, a linear regression is performed on the experimentally measured k-factor values where the resulting equations and the corresponding model coefficients are shown in Fig. 18 and Table 9, respectively. The resulting values of $R^2$ and RMSE are 0.420 and 0.0131 for the circular model, and the corresponding values for the sinusoidal model are 0.564 and 0.0098, respectively.

On closer examination of Fig. 18a, it can be seen that the resistance k-factor is decreased with increasing power and decreasing feed rate for the circular beam wobbling. However, this effect decreases with increasing frequency. For a constant frequency of $f = 249$ Hz ($f'_w = 1$), the resistance k-factor does not vary significantly with respect to power and feed rate.

The resistance k-factor for the sinusoidal beam wobbling, as shown in Fig. 18b, exhibits a slightly different behaviour compared to the circular beam wobbling. For low power values the resistance k-factor decreases with decreasing feed rate, but when the power is increased there is a shift in behaviour. For high power values the resistance k-factor are instead increasing with decreasing feed rate. For the sinusoidal beam wobbling it can also be seen that the resistance k-factor
Fig. 18. Resistance k-factor for circular (a) and sinusoidal (b) beam wobbling. The black circles represent experimentally measured values and the coloured surface represents a linear regression model fitted to the data, which is described by the corresponding equation.

Table 9
Linear regression coefficients for resistance k-factor for circular and sinusoidal beam wobbling.

<table>
<thead>
<tr>
<th></th>
<th>$k_1$</th>
<th>$k_2$</th>
<th>$k_3$</th>
<th>$k_4$</th>
<th>$k_5$</th>
<th>$k_6$</th>
<th>$k_7$</th>
<th>$k_8$</th>
<th>$k_9$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circular</td>
<td>1.067</td>
<td>-0.0129</td>
<td>-0.00494</td>
<td>0.0473</td>
<td>-0.0270</td>
<td>-0.0133</td>
<td>-0.0177</td>
<td>0.0206</td>
<td>-0.0541</td>
</tr>
<tr>
<td>Sinusoidal</td>
<td>1.051</td>
<td>-0.0218</td>
<td>0.0418</td>
<td>-0.0148</td>
<td>-0.00333</td>
<td>0.0365</td>
<td>-0.0125</td>
<td>0.0318</td>
<td>-0.0413</td>
</tr>
</tbody>
</table>

Table 10
Linear regression coefficients for total pore volume for circular and sinusoidal beam wobbling.

<table>
<thead>
<tr>
<th></th>
<th>$v_1$</th>
<th>$v_2$</th>
<th>$v_3$</th>
<th>$v_4$</th>
<th>$v_5$</th>
<th>$v_6$</th>
<th>$v_7$</th>
<th>$v_8$</th>
<th>$v_9$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circular</td>
<td>0.158</td>
<td>0.0589</td>
<td>-0.232</td>
<td>0.00638</td>
<td>0.201</td>
<td>-0.919</td>
<td>0.288</td>
<td>-0.0614</td>
<td>-0.00538</td>
</tr>
<tr>
<td>Sinusoidal</td>
<td>0.862</td>
<td>0.324</td>
<td>0.0391</td>
<td>0.0533</td>
<td>-0.0307</td>
<td>0.170</td>
<td>-0.534</td>
<td>0.100</td>
<td>0.262</td>
</tr>
</tbody>
</table>

4. Discussion

From the experimental results presented in Section 3, some key findings, correlated to laser welding of Ni-plated Cu and Hilumin plates using beam wobbling, can be stated.

The in-process temperature is more affected by changes in frequency for the sinusoidal beam wobbling compared to circular beam wobbling. Two possible reasons for this have been identified: (1) The effective area, i.e. the area where the laser spot interacts with the base material for one oscillation of the wobbling pattern, is larger for circular beam wobbling compared with sinusoidal beam wobbling. This means that the laser power is distributed over a larger area, which leads to a lower temperature gradient for circular beam wobbling. This may explain that the measured in-process temperatures show greater variation with respect to the wobbling frequency for sinusoidal beam wobbling. (2) The difference between the maximum and minimum absolute velocity of the laser spot increases with increasing frequency for sinusoidal beam wobbling, while this difference is constant for circular beam wobbling. This means that the difference in maximum and minimum energy input also increases with increasing frequency for sinusoidal beam wobbling. This should mean that the temperature gradient increases with increasing frequency for sinusoidal beam wobbling and can then explain that the in-process temperature is more affected by changes in frequency for sinusoidal beam wobbling. The reasoning that sinusoidal beam wobbling can be associated with a larger temperature gradient is shown experimentally in [25]. Worth noting, however, is that power modulation is used in the present study, which also affects the temperature gradients.

Fig. 19. Longitudinal CT slices in the middle of the weld seam for sampling points 5 (a), 14 (b) and 8 (c).

The total pore volume for the sinusoidal beam wobbling, as shown in Fig. 20b, shows a relatively constant behaviour with only a sharp increase at highest power and feed rate. Furthermore, the total pore volume is not significantly affected by wobbling frequency.

The minimum total pore volume, for circular and sinusoidal beam wobbling, are 0.038 mm$^3$ and 0.009 mm$^3$, respectively. These observations correspond to sampling points 5 and 21 with welding parameters according to Table 3.
The in-process temperature is generally increased with increasing power and decreasing feed rate, both for circular and sinusoidal beam wobbling. This is easily explained by the larger energy input associated with an increased power and a decreased feed rate. Therefore, consideration must be given to how these parameters are set in order to not violate any temperature requirements. Related to the findings regarding the in-process temperatures, however, it is worth mentioning that there is a relatively large measurement uncertainty for the in-process temperature measurements. Due to the wobbling patterns, there are temperature gradients present that make it difficult to place the measuring point exactly where the maximum temperature appears. In addition, a varying gap between the plates, and thus varying contact conditions, can cause some scatter in the measured in-process temperatures. Although actions have been taken to minimize the gap between the plates, small variations can contribute to some uncertainty in the measurements. Due to these uncertainties, more repeated temperature measurements would be beneficial. Moreover, in real-world production scenarios it is also essential to reduce the gap between the plates to ensure a sufficient joint between the cell and the busbar.

Generally, the welding depth increases with increasing power and decreasing feed rate, both for circular and sinusoidal beam wobbling. Furthermore, large variations in welding depth have been observed along the longitudinal direction of the weld seam, even though power modulation has been used. This indicates that the utilized power modulation has not given the desired impact. After all, the purpose of the power modulation is to spatially smoothen out the energy input and thus reduce the variation in welding depth. Therefore, more research needs to be done on how different power modulation strategies can be used to reduce the variation of welding depth in beam wobbling of thin dissimilar material joints.

The interface width is significantly larger for the circular beam wobbling compared with the sinusoidal beam wobbling. A conceivable reason for this is partly that the effective area for the circular beam wobbling is larger compared with the sinusoidal beam wobbling. Another reason is that the wobbling pattern overlaps to some extent for circular beam wobbling and thus creates a larger melt pool, compared to sinusoidal beam wobbling where there is no overlap. Similar observations have been reported in [24]. Worth to notice though, is that power modulation have been used in the present study, which also affects the interface width. However, this difference in power modulation results in a difference of only 8% in energy input, which is considered to be small enough to make it possible to compare the two strategies.

The joint shear strength generally increases with decreasing feed rate and increasing power for both circular and sinusoidal beam wobbling. The larger energy input associated with a decreased feed rate and an increased power explains this. A larger energy input, thus results in a larger melt volume and thus a larger contact area that can withstand a larger force.

With an increasing wobbling frequency the joint shear strength is increased for circular beam wobbling but decreased for sinusoidal beam wobbling. A potential explanation for this, is that an increased wobbling frequency leads to a more dense wobbling pattern, i.e. a smaller distance $d$ according to Eq. (6), and for the circular beam wobbling this also leads to a larger overlap in the wobbling pattern. This larger overlap may lead to a larger melt pool which simultaneously gives a larger melt volume and thus a larger contact area. The reason why the joint shear strength decreases with increasing wobbling frequency for sinusoidal beam wobbling is believed to be that the burn-through in the bottom plate increases with increasing frequency, creating defects in the joint that degrade its strength. A possible explanation for this is that when the frequency is increased, the wobbling pattern becomes more compressed, which increases the size of the melt pool. At the same time, the lowest absolute velocity for the sinusoidal beam wobbling is not affected when the frequency is increased. In contrast to circular beam wobbling where the lowest absolute velocity increases as the frequency increases. For sinusoidal beam wobbling, this means that a high energy is supplied to a large melt pool, which increases the risk of burn-through.

The resistance k-factor is decreased with increasing power and decreasing feed rate for the circular beam wobbling, but this effect decreases with increasing frequency. Like the explanation for joint shear strength, the decreased resistance k-factor can be explained by the larger energy input associated with a decreased feed rate and an increased power which results in a larger melt volume and thus a larger contact area. The phenomenon that the resistance k-factor is less affected by changes in feed rate and power for an increased wobbling frequency can be understood by the denser wobbling pattern generated by a high frequency which makes the contact area less sensitive of changes in feed rate and power.

For the sinusoidal beam wobbling the resistance k-factor decreases with decreasing feed rate, for low power values, but for high power values the resistance k-factor is increasing with decreasing feed rate. The greater amount of burn-through, associated with high power and low feed rate, obtained for sinusoidal beam wobbling may be the reason for this behaviour. When the bottom plate is burned through, the keyhole collapses which leads to a start over for the keyhole formation and thus a reduction in connection area. Furthermore, defects, such as porosities, are expected to appear which also may impair the conductivity of the joint. Worth noting, however, is that all sampling points show relatively good values for the resistance k-factor, and do not differ much from each other. Therefore, it could be difficult to find the right trends.

![Fig. 20. Total pore volume for circular (a) and sinusoidal (b) beam wobbling. The black circles represent experimentally measured values and the coloured surface represents a linear regression model fitted to the data, which is described by the corresponding equation.](image-url)
This could be improved by increasing the accuracy of the resistance measurements, for example by increasing the measurement current.

For circular beam wobbling the total pore volume and material mixing are significantly increased with increasing laser power and wobbling frequency. This can possibly be explained by the increasing material flow, due to both a high power and a high absolute velocity, associated with a high wobbling frequency. For sinusoidal beam wobbling this behaviour is not observed, due to a more stable material flow. There, the total pore volume is mostly affected by changes in power and feed rate and not significantly affected by the wobbling frequency. The maximum total pore volume is observed for the lowest feed rate and highest power, which seems reasonable.

5. Conclusions

In the present study, circular and sinusoidal beam wobbling are implemented for laser welding of dissimilar material cell-to-busbar joints, in order to investigate how different laser welding parameters affect the joint quality. Laser welding experiments are performed, where Ni-plated Cu and Hilumin plates are joined in an overlap configuration, using beam wobbling and power modulation. The joint quality is evaluated using joint geometry analysis, shear strength tests, CT-scanning and electrical resistance measurements of the joints. From the experimental evaluation some conclusions are drawn:

- For circular beam wobbling the total pore volume and material mixing are increased with increasing laser power and wobbling frequency. However, for sinusoidal beam wobbling, variations in wobbling frequency had minimal impact on total pore volume.
- For similar process parameters, circular beam wobbling gives a larger interface width and joint shear strength in comparison with sinusoidal beam wobbling.
- Increasing laser power and decreasing feed rate improve interface width, joint shear strength, and resistance k-factor in both circular and sinusoidal beam wobbling. However, this effect is limited by a threshold where burn-through becomes a risk.
- For an increasing wobbling frequency an increased joint shear strength is observed for circular beam wobbling, but for sinusoidal beam wobbling a decrease is observed.

In future research work, a more detailed investigation of how to reduce the variation of welding depth, using power modulation, should be considered. Future work can also be to increase the understanding of how different process parameters affect other quality measures that are not considered in this study, e.g. the formation of undercutts, hot cracks, IMC or spatter. Furthermore, numerical investigations of the complex phenomena found during laser welding of dissimilar materials using beam wobbling are also recommended as future work.

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CRediT authorship contribution statement

Andreas Andersson Lassila: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. Dan Lön: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. Tobias Andersson: Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization. Wei Wang: Writing – review & editing, Methodology, Investigation, Conceptualization. Rohollah Ghasemi: Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.optlastec.2024.111155.

References


