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² The home page of the website should contain the generic European flag and the FP7 logo which are available in electronic format at the Europa website (logo of the European flag: http://europa.eu/abc/symbols/emblem/index_en.htm ; logo of the 7th FP: http://ec.europa.eu/research/fp7/index_en.cfm?pg=logos). The area of activity of the project should also be mentioned.
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1 Introduction

The QCOALA integrated demonstrator for the battery application is in essence the culmination of one of the two major objectives of the QCOALA project (together with the integrated demonstrator for the solar cell application). It brings together all parts of work in this area of the project starting with the definition of the end user requirements (WP1), the collected experiences of intelligent laser welding (WP3), the process monitoring system (WP4) and finally the Eddy Current (EC) and Digital Radiography inspection systems (WP5). All this has been assembled in the facilities of TWI Ltd for the demonstration activity.

This deliverable report describes the work performed under the headings of: the Laser Welding Platform, the Weld Monitoring System, the EC and the DR Inspection systems.

2 Laser Welding Platform

2.1 Laser Equipment

The laser used in the trials was a combination of a pulsed q-switched green wavelength laser (532nm wavelength) and a continuous wave (cw), high power, infrared (IR) laser (1070nm wavelength). Specifically, the laser equipment was:

- A CW IPG YLS 5000 Yb-fibre laser (1070nm wavelength).
- A q-switched pulsed Rofin 53 PowerLine L 100 Nd:YAG laser (532nm wavelength).

The emitted laser beams from the two laser sources were delivered through the same Precitec dual-wavelength processing head. The focusing lens of the dual-wavelength Precitec head was a special design for QCOALA and a first approach for combining the particular beam sources used. The unit was equipped to receive two optical fibres to deliver the beams, to combine them and then to focus them through the same lens. The delivery of the two laser beams delivered through the same dual-wavelength processing head made the welding platform compatible with an industrial manufacturing setup.

The Precitec process head was set in a fixed position, at 15° from the vertical position to protect the laser source from problems caused by back-reflection from the Cu surface at non-optimised conditions.

Figure 1 shows images of the laser sources and the Precitec process head. Some significant specifications of the laser equipment are reported in Table 1.
Figure 1 Images of the IR Yb-fibre laser from IPG, the q-switched green laser and the dual-wavelength process head:

a) 5kW CW Yb-fibre laser (1070nm wavelength);
b) 100W q-switched Nd:YAG laser (532nm wavelength);
c) Precitec dual-wavelength process head.
Table 1 Specifications of the IPG Multi-mode Yb-fibre laser and Rofin 53 PowerLine L 100 q-switched green laser

<table>
<thead>
<tr>
<th>Laser</th>
<th>IPG Multi-mode Yb-fibre laser</th>
<th>Rofin 53 PowerLine L 100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>1070 nm</td>
<td>532 nm</td>
</tr>
<tr>
<td>Operation mode</td>
<td>Continuous wave</td>
<td>Pulsed q-switched performance at 10kHz</td>
</tr>
<tr>
<td>Pulse width (ns)</td>
<td>-</td>
<td>100</td>
</tr>
<tr>
<td>Peak power (kW)</td>
<td>-</td>
<td>&gt;80</td>
</tr>
<tr>
<td>Average power (W)</td>
<td>5000</td>
<td>100</td>
</tr>
<tr>
<td>Rep.rate (kHz)</td>
<td>-</td>
<td>10</td>
</tr>
<tr>
<td>Delivery fibre diameter (μm)</td>
<td>150</td>
<td>100</td>
</tr>
<tr>
<td>Process head collimating lens focal length (mm)</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Focussing lens focal length (mm)</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Calculated beam spot size (μm)</td>
<td>150</td>
<td>100</td>
</tr>
</tbody>
</table>

The focusing lens of the dual-wavelength processing head was protected from damage by fume and spatter, using an air-knife, and a semi-consumable cover slide situated between the lower surface of the focusing lens and the workpiece.

The dual-wavelength head was equipped with adjustments which provided the option to change the position of the minimum focused beam diameter from both wavelengths, in the Z direction, as well as to offset the 532nm and 1070nm wavelength beams in the X-Y plane. This control was used to introduce a separation between the two beams. Figure 2 shows an image of the welding platform.
2.2 Manipulation

The dual-wavelength head (Figure 1c) was mounted on a 6-axis Kawasaki JS-030 robot; the robot was used to manipulate the Z position of the dual-wavelength head and to set the angle of incidence between the laser beam and the workpiece. The workpieces were moved during welding on an Aerotech X-Y table (Figure 3), programmable, to trigger the release of both 532nm and 1070nm wavelength laser beams separately or combined.

![Image of dual-wavelength head mounted on robot](image)

**Figure 3** Aerotech X-Y table used for experimental trials.

2.3 Fixturing and gas shielding

A mechanical top-down clamping fixture, designed and manufactured by Safel, was used to lap-weld the Cu and Al battery terminals (6mm thickness) Cu connector plates (1mm thickness). Images of the clamping fixture are shown in Figure 4.

![Image of clamping fixture](image)

**Figure 4** Side-view (a) and top-view (b) images of pneumatic top-down clamping fixture designed and manufactured by Safel.
The welding process was shielded by argon gas, delivered to the workpiece through two Cu tubes, positioned facing each other but oriented on the welding area.

The welding platform is computer-controlled, the complete process is partly automated.

2.4 Approach

The laser welding platform was developed for two material combinations of the battery terminals: Cu (1mm) to Cu (6mm) and Cu (1mm) to Al (6mm). The end-user (the partner Volkswagen) requirements included the achievement of Cu to Cu and Cu to Al lap-welds with penetration depths greater than 1mm, defect-free welds and welding speeds of the order of 6m/min.

The welding fixture carried 12 individual battery cells electrically connected to form a module unit. Specifically, Cu busbars were lap-welded to Cu or Al battery terminals attached to the battery cells and Figure 5 shows an image of the 12 battery cells assembled to compose the module unit. Suitable process windows (reported in D3.4 deliverable report ‘Welding electric battery interconnections using a cw-pulsed laser platform’) were developed to put into practice the production of lap-welds for the battery demonstrator.

![Battery module](image)

*Figure 5* Image of the 12 battery cell module used for the demonstration.
For the verification of process monitoring system, EC and DR inspection systems, the following samples were produced for quality evaluation:

- Joint between the busbar and the terminal pin.
- No joint between the busbar and the terminal pin.
- Weld top-bead defects, such as melt ejections and blow holes (typical of the Cu-to-Cu combination of materials).
- Weld profile defects such as crack formation and porosity (typical of the Cu-to-Al combination of materials).

2.5 Results

The lap-weld experiments performed to join Cu or Al battery terminals (6mm thickness) and Cu busbars (1mm thickness) were evaluated by focusing on the quality of the weld profile and on the productivity requirements addressed by the end-user Volkswagen. The quality of welds was also benchmarked against the EN ISO standard 13919-2:2001, ‘Welding – Electron and laser beam welded joints – Guidance on quality levels for imperfections, Part 2’ (details reported in reported in D3.4 deliverable report ‘Welding electric battery interconnections using a cw-pulsed laser platform’).

2.5.1. Weld quality evaluation

It should be noted that the laser technology is a new approach for welding Cu and Al for electrical connection in battery terminals, therefore, it has not been implemented for high volume production environments yet (existing joining procedures include mechanical screwing) and currently no in house quality criteria for such joints fully exist at Volkswagen.

For this application, important evaluation criteria include minimum spatter from the surface of the welds (to maintain a clean production environment), lack of blow holes in the case of Cu to Cu welding and minimised formation of cracks in the case of Cu to Al dissimilar welding (the latter due to intermetallic phase formation). In addition, for maximised strength and electrical conductivity, another criterion was the width of the joint at the interface.

Figure 6 and Figure 7 respectively show micrographs of Cu to Cu (a) and Cu to Al (b) welded samples representative of good quality joints.

**Figure 6** Representative of a good quality joint:
(a) Micrographs of weld top-bead;
(b) transverse cross section of Cu to Cu lap-welded sample.
**Figure 6 (continued)** Representative of a good quality joint:
b) transverse cross section of Cu to Cu lap-welded sample.

**Figure 7** Micrographs of weld top-bead (a) and transverse cross section (b) of Cu to Al lap-welded sample, representative of a good quality joint.
Typical defects that were observed during the development stage of the welding platform (when parameters were outside the successful process window) were the following:

- Blow holes and melt ejections for Cu to Cu welds (Figure 8).
- Crack formation (Figure 9a) and porosity (Figure 9b) at the joint interface for Cu to Al welds.

**Figure 8** Top-bead micrograph of Cu to Cu weld, showing an example of blow hole formation.

**Figure 9** Cu to Al welds, showing an example of:
- a) Crack formation;
- b) Sub-surface porosity.

### 2.6 Discussion

The welding platform produced welds of good quality for both joint configurations. The quasi-optimised parameters provided repeatable results. The generated data is reported in D3.4 QCOALA deliverable report. Additional tests were made with the demo welded battery modules.

The quasi-optimised conditions achieved for Cu to Cu lap-welds on battery dummies met the main requirements set by VW for the battery application, which included a weld penetration depth greater than 1mm and welding speeds of the order of 6m/min. Comparing the weld quality of the quasi-optimised condition, shown in Figure 6, against the criteria of the ISO 13919-2, it was possible to make the following observations:

- No cracks occurred.
- No surface blow holes were detected.
- Interface weld width was greater than 0.8mm.
- Crack formation did not occur, (at least after viewing under a magnification of 1mm).
- Subsurface porosity was not observed.
The quasi-optimised parameters achieved for Cu to Al lap-welds of battery dummies met the main productivity requirements addressed by VW for the battery application, which included a weld penetration depth greater than 1mm and welding speeds of the order of 6m/min. Comparing the weld quality of micrographs shown in Figures 7 against the criteria of ISO 13919-2, it was possible to make the following observations:

- Crack formation was not greater than 0.4mm\(^2\).
- No surface blow holes occurred.
- In terms of subsurface porosity, the maximum pore size was less than 0.45mm.
- Interface weld width was 0.6mm (the minimum value was 0.8mm weld width).
- In the absence of radiographs of the welds, the sum of the projected area of the sub-surface porosity was estimated taking into consideration the pores' distribution in the longitudinal section taken in the middle of the weld (Figure 29b), which was 0.03mm\(^2\).

2.7 Summary and conclusions

Extensive trials were made to establish the connection of busbars to terminals of battery cells. A platform was built to implement the results in a semi-automated operation environment.

The battery module produced using the welding platform was assessed in collaboration with the QCOALA partners Safel and Volkswagen.

The reported methods for laser welding busbars to terminals of battery cells were successful. From an electrical conductivity point of view, this will need to be fully validated in-house at Volkswagen. In general, it is felt operation that manufacturing battery cells in a production line is possible.

2.8 Recommendations

During the development of a welding platform for the battery application, the overall goal was to assess the combined wavelength system in terms of weld quality, productivity and weld penetration depth. Given a lack of published quality criteria for laser welding battery terminals, the approach used was to classify, where possible, the welds to ISO 13919 and to add other criteria thought to be important, such as the degree of surface blowholes observed and weld width at the joint interface.

It is suggested that, in order to understand better the interaction of the two beams with the material, high speed video is made of the welding process.

3 Weld Monitoring System (WMS)

3.1 Equipment

The weld monitoring system is a proof-of-concept prototype that was developed during this project. The weld monitoring system consists of sensors, electronic equipment and software, as depicted in Figure 10. The system monitors laser welding online by high-speed videography and spectrometry.
Figure 10 Weld monitoring system architecture.

A camera images the weld pool and a spectrometer analyses emitted radiation from the keyhole continuously during weld. The camera and spectrometer are integrated in a processing head as shown in Figure 11. The user interface, as shown in Figure 12, assists with data acquisition during welding and furthermore tracking by allowing to later load data corresponding to a particular weld.
3.2 Approach

The objective of the weld monitoring system is to detect weld imperfections with regard to penetration depth. The pursued approach is the monitoring of the weld pool surface geometry. Quality control will be performed as shown in Figure 13.
To investigate how suitable the weld pool geometry is, the following experiment was conducted by ILT and TWI. The experiment contains the following steps:

1. Integration of the weld monitoring system into the PRECITEC dual wavelength head.
2. Welding trials while monitoring with weld monitoring system.
   2.1. Investigation of lack of fusion detection in Cu to Cu and Cu to Al joints
       2.1.1. Nominal values
       2.1.2. Creation of lack of fusion by decreasing the laser power
       2.1.3. Creation lack of fusion by increasing the feed rate
   2.2. Investigation of penetration depth measurement in Cu to Cu and Cu to Al joints
       2.2.1. Stepwise variation of laser power by ±10% in Cu to Cu welds.
       2.2.2. Stepwise variation of feed rate by ±10% in Cu to Cu welds.
       2.2.3. Stepwise variation of laser power by ±10% in Cu to Al welds.
       2.2.4. Stepwise variation of feed rate by ±10% in Cu to Al welds.

In section 3.3 a selection of significant results are presented.

3.3 Results

3.3.1. Nominal welding parameters

Welding parameters that were determined by process development in WP3 are called nominal welding parameters.

The nominal set values of the first laser source are, with index IR denoting the laser at the wavelength of 1070 nm and therefore emitting radiation in the infrared spectrum, P denoting laser power and Δz defocus, i.e. shift of focal plane upwards from the work piece surface,

$$F_{IR} = \begin{cases} 5000 \text{ W for Cu/Cu} \\ 4000 \text{ W for Cu/Al} \end{cases} \quad \text{and } \Delta z_{IR} = 2 \text{ mm}.$$  

The nominal set values of the second laser source are, with index GR denoting the laser at the wavelength of 532 nm and therefore emitting radiation visible green, $\bar{P}$ being the average power, $T_p$ pulse duration, $f_p$ pulse frequency,

$$\bar{P}_{GR} = 60 \text{ W}; \quad T_{p,GR} = 4 \mu s; \quad f_{p,GR} = 10 \text{ kHz} \quad \text{and } \Delta z_{GR} = 0.$$  

The remaining welding parameters feed rate $v$ and shielding gas flow $V$ are

$$v = 6 \text{ m/min and } V = 20 \text{ l/min (Ar).}$$
3.3.2. Detection of lack of fusion

Weld pool geometry was monitored via high-speed videography in the experimental setup as presented in 3.1. To induce lack of fusion the laser power was set to approximately half of the nominal value.

In welding of Cu to Cu interconnects a decrease in weld pool size was observed for all of the samples with lack of fusion, as tabulated in Error! Reference source not found.2.

Table 2 Welding parameters and weld pool area of Cu to Cu.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Condition</th>
<th>Top partner penetrated</th>
<th>Bottom partner penetrated</th>
<th>Weld pool area (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>68-208</td>
<td>Nominal P=5000 W</td>
<td>Yes</td>
<td>Yes</td>
<td>2.87</td>
</tr>
<tr>
<td>68-209</td>
<td>Nominal P=5000 W</td>
<td>Yes</td>
<td>Yes</td>
<td>2.56</td>
</tr>
<tr>
<td>68-210</td>
<td>Nominal P=5000 W</td>
<td>Yes</td>
<td>Yes</td>
<td>2.55</td>
</tr>
<tr>
<td>68-212</td>
<td>P=2750 W</td>
<td>Yes</td>
<td>No</td>
<td>0.90</td>
</tr>
<tr>
<td>68-213</td>
<td>P=2750 W</td>
<td>Yes</td>
<td>No</td>
<td>1.12</td>
</tr>
<tr>
<td>68-214</td>
<td>P=2750 W</td>
<td>Yes</td>
<td>No</td>
<td>1.15</td>
</tr>
</tbody>
</table>

In welding of Cu to Al interconnects, the laser power decreased to approximately half of the nominal value as well. In contrast to Cu to Cu welds there was no weld where the top partner was penetrated while the bottom one was not. The welds are tabulated in Error! Reference source not found..
Table 3 Welding parameters and weld pool area Cu to Al.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Condition</th>
<th>Top partner penetrated</th>
<th>Bottom partner penetrated</th>
<th>Weld pool area (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>68-321</td>
<td>Nominal P=4000W</td>
<td>Yes</td>
<td>Yes</td>
<td>4.30</td>
</tr>
<tr>
<td>68-322</td>
<td>Nominal P=4000W</td>
<td>Yes</td>
<td>Yes</td>
<td>4.36</td>
</tr>
<tr>
<td>68-323</td>
<td>Nominal P=4000W</td>
<td>Yes</td>
<td>Yes</td>
<td>4.14</td>
</tr>
<tr>
<td>68-328</td>
<td>P=2675 W</td>
<td>No</td>
<td>No</td>
<td>--</td>
</tr>
<tr>
<td>68-329</td>
<td>P=2675 W</td>
<td>No</td>
<td>No</td>
<td>--</td>
</tr>
<tr>
<td>68-330</td>
<td>P=2675 W</td>
<td>No</td>
<td>No</td>
<td>--</td>
</tr>
<tr>
<td>68-331</td>
<td>P=2700 W</td>
<td>1/3</td>
<td>1/3</td>
<td>1.13</td>
</tr>
</tbody>
</table>

In the previous tables where the top partner of the weld was not penetrated a slim seam was observed whose width is only a fraction of the value usually observed.

3.3.3. Measurement of penetration depth

Weld pool geometry was monitored via high-videography in the experimental setup presented in section 3.1. Laser power and the feed rate were varied in steps of 10%. The width, length and area of the weld pool are plotted for Cu to Cu overlap welds in Figures 14 and Cu to Al welds in 15, respectively. The nominal welding parameters are listed in subsection 3.3.1.
Figure 15 Change in weld pool geometry during welding of Cu to Al: Welding parameters were varied in steps of 10% from the nominal welding parameters.

3.4 Summary and conclusions

- **Weld monitoring system** is a proof-of-concept prototype that has been developed during this project. It consists of sensors, electronic equipment and software. The objective of the weld monitoring system is to detect any weld imperfections with regard to penetration depth. The pursued approach is the monitoring of the weld pool surface geometry and radiation emitted from keyhole.

- **Weld pool geometry** has been found by experiments to change when laser power and feed rate were varied. This indicates that it changes with penetration depth.

**Resolution of penetration depth measurement**: It is assumed that penetration depth \( \hat{h} \) is linear to weld pool area \( A \), which is valid at least in a small neighbourhood of nominal welding parameters

\[
\hat{h} = c \cdot A,
\]

where \( c \) is the proportionality factor. The measurement uncertainty of the penetration depth \( \Delta \hat{h} \) can be estimated by the measurement uncertainty of the welding area \( \Delta A \), since

\[
\hat{h} \pm \Delta \hat{h} = c \cdot (A \pm \Delta A).
\]

Therefore

\[
\Delta \hat{h} = c \cdot \Delta A
\]

and

\[
\frac{\Delta \hat{h}}{\hat{h}} = \frac{c \cdot \Delta A}{c \cdot A} = \frac{\Delta A}{A}.
\]

The weld pool area measurement uncertainty is estimated as \( \Delta A = 0.25 \text{ mm}^2 \) based on Error! Reference source not found.2, Error! Reference source not found.3.
The penetration depth measurement uncertainty is estimated to 0.25 mm$^2$ for Cu to Al joints and to 0.25 mm$^2$ for Cu to Cu joints, respectively. For comparison the output instability of a similar infrared laser is 2.5%.

### 3.5 Recommendations

- For any application of the weld monitoring system the implemented architecture was found fit and is recommended.
- For further research it is recommended to pursue calculation and simulation of the weld pool geometry. Even though the underlying mechanisms are known to be complex, simple models based on heat conduction and ignoring convection of the molten material might be applied in some regimes.
4 Digital Radiography (DR) Inspection System

4.1 Introduction

The QCOALA battery terminal digital radiography inspection system utilises a combination of innovative mechanical design with fully customised software modules to allow for accept/reject analysis of the component under inspection. The system has been designed with the in-line production environment in mind with the prototype system produced (Figure 16) being easily adapted and refined for manufacture for this requirement.

Figure 16 Digital radiography prototype system.

The system as designed has been validated with the exposure and analysis of a number of samples as provided by TWI, created with varying parameters using the green mix laser. The technical specification of the DR inspection system, the route to and the results of the demonstration are discussed below.

4.2 Equipment

The mechanical sub-system consists of:

- A motorised linear slide for automation of the component under inspection. The travel range on this is 0-450mm with a positional accuracy of +/- 25 microns.
- Radiographic Detector mounting spokes with fine tuning capabilities of +/- 15° linear rotation.
- Sample under inspection holding tray with 40mm linear adjustment for accurate sample positioning.
- Load bearing c-frame with x-ray head mounting arrangement at 45° positioning with capability for beam alignment changes to full detector spoke range and further should the component under inspection change.
- Mounting base plate for all other mechanical sub-assemblies for easy integration into a production environment.
X-ray head and control system specifications are the following:

- 30kV – 120kV constant potential x-ray generator.
- 50 micron micro-focus focal spot.
- 10μA - 350μA current rating.
- Glass window.
- Computer controlled software interface with safety warning.

Radiographic Detector specifications are the following:

- 25 x 50mm active plane.
- 512 x 1024 photodiode silicon matrix on 48 μm centres.
- 524,288 pixels with 10 lp/mm resolution.
- Frame rate variation between 0.01 – 4.5 Hz.

Radiographic Radiation shielding/safety features consist of:

- TWI Laser cell designated area for demonstration as specified in Local rules for the demonstration.
- 3 tier colour coded safety warning beacon.

DR Computing platform and software consist of:

- Dedicated 8GB 64Bit effective 8 core (4 core with built in hyper-threading) laptop with windows operating platform.
- QCOALA Battery NDT DR Software V1.0;
  - Product profile and technique generation
  - Defect acceptable tolerance set-up and definition capability.
  - Automated image acquisition.
  - ADR functionality.
  - Automation interface for control between sub-assemblies.
  - Image archiving and retrieval for storage and audit purposes.

### 4.3 Approach

For the battery terminal DR inspection demonstration the sample cells had undergone laser welding prior to the demonstration and remained fitted within the base plate of the welding clamping system to ensure that the beam angle and the detector positioning for the inspection remained true to requirement.

The steps taken to sufficiently demonstrate the capability of the system consisted of:

1. Loading the sample, contained within the clamping system base plate, onto the sample shelf of the inspection system.
2. Loading the QCOALA NDT DR Inspection software up onto the system laptop.
3. Demonstrating the loading, editing, saving and confirmation of the radiographic technique form which was optimised for the inspection of the battery. The potential for commercialisation into other fields and components was demonstrated with the customisable technique fields.
4. Homing the automation system so that the datum point is set and the inspection could be carried out accurately. Further demonstrating the automation capabilities by setting step sequences for the slide table to follow.
5. Demonstrating the capability of the software to set tolerance values, ADR values, pre and post-signal processing selections and region of interest (ROI).
6. Acquiring an image using the QCOALA battery terminal DR inspection system and loading the resultant image. After acquiring and loading this image the pre-set filters, processing and ADR was applied to the image.
7. Demonstrating the resultant histograms and report from the image analysis and the accept/reject decision making facility.
8. Demonstrating the archiving and retrieval mechanisms within the software for post archiving review or audit purposes.

4.4 Results

Over the duration of the project CIT have received a variety of samples from TWI consisting of dummy battery terminals of both Cu-Al and Cu-Cu manufactured using the green mix laser and a variety of parameters to simulate acceptable and unacceptable welds. The radiographic analysis of the supplied samples consisted of various tests to develop the most appropriate technique for each sample configuration. Each sample was separated into one of the two configurations: Cu to Cu or Cu to Al and the inspection conducted from this point onwards with image acquisition and then ADR analysis for the pass/fail decision.

Sample G324 (Figure 17) was supplied by TWI and was representative of a visually good weld for a Cu to Al dummy terminal. The radiograph image, produced after exposing sample G324 to x-ray radiation (Figure 17b), has a lighter weld with lower measurable radiographic density than the Cu surrounding it due to the combination of the Al with the Cu parent material along the length of the weld.

![Figure 17](image)

**Figure 17** Top-surface of Cu to Al sample G324 (a) and radiograph image of the weld.

Although the weld does not possess the same level of homogeneity as the Cu-Cu welds that where inspected throughout the project duration (this is as expected with the difference in metals comprising the weld) the level of change in the greyscale along the radiograph suggests that the weld is sound and shows uniformity along the length of it. This proves an acceptable contact has been created between the two metals and the manufacturing process has been a success. When ADR was applied to this exposure shot the sample was categorised as a pass component.

The difference between the uniform nature of an acceptable weld when inspected using digital radiography and an unacceptable weld is highly evident. The clear advantages of the QCOALA DR inspection system lie in the ability of the image processing algorithms to define acceptable and unacceptable flaws that may not be as obviously detectable with visual inspection alone.

As shown with sample G325 (Figure 18) when inspected using the QCOALA battery terminal system the radiograph produced (Figure 18b) has some visual differences from the weld previously commented upon but has other areas that are very similar in appearance. After applying ADR to the weld radiograph the automated decision making process analysed the percentage of acceptable to unacceptable flaws and categorised this sample as a fail.
The radiographic results from the Cu-Cu sample exposures where also analysed using the QCOALA battery terminal DR inspection system and examples of a pass and fail sample are provided below.

The radiograph produced after exposing sample G340 (Figure 19) shows that the weld is consistent along the length of it from a visual inspection and suggests, due to the lack of any areas of greater or less radiographic density, that there are no sub-surface porosity or weld failures detectable. The ADR analysis that was run on this radiograph reported very little variation along the length of the weld and produced a pass categorisation.

In contrast to sample G340 the image produced after exposing sample G331 (Figure 20) shows that the weld has consistent defects throughout the length of it. The areas of high radiographic density correlate to the visual imperfections on the sample of numerous holes and pits along the length of the weld.

There are faint changes in density along the weld that suggest porosity below the surface of the sample. Notably there are also areas on the right hand side of the radiograph, along the top of the weld and around the middle, of areas that show an excess build-up of Cu where the molten metal has over run during manufacture. The application of the ADR functionality confirms that this is a very poor quality of weld which is categorised as a fail.
The consistency of the results generated and the ADR functionality applied to determine the acceptance of any battery terminal under inspection is repeatable; the result being generated from the algorithmic processes that are applied. The archiving capability of the system allows these images and the associated analysis reports to be securely archived for future reference, particularly for fault failure analysis and audit purposes.

4.5 Summary and conclusions

- The inspection capability that has been reached with the QCOALA battery terminal application has the potential to fill a void in the non-destructive testing field in regards to the inspection of thin gauge welds. For the means of commercialisation the system hardware may require further development at the detection end to fully maximise the capability of the system software.
- The use and integration within the software of the image processing algorithms, filtering and pre/post processing of the radiographic images have created successful software modules that can be applied to a variety of applications that fulfils and reaches past the scope of this project.
- The acceptable/unacceptable criteria has been determined by the use of processing algorithms that determine acceptable flaw size that have been written into the custom QCOALA battery terminal software application. The accuracy and degree of acceptable defect size detection is currently at an acceptable level for certain applications although there is a requirement for further definitions should the intended component under inspection evolve.

4.6 Recommendations

- Further DR inspection trials are advisable to reduce the size of defects detectable. This could include further development of the ADR functionality of the software to include other defect categories.
- The system hardware as supplied for the battery demonstration could undergo further development to provide a production line ready inspection system with full integration between both the other subsystems and the individual line set-up per customer requirement.
- The system as currently supplied may require optimisation to fulfill the production speeds required in situ.
- Research into further application possibilities could be explored to further the commercial viability of the QCOALA battery terminal inspection system.

5 Eddy Current (EC) Inspection System

5.1 Introduction

The use of Eddy Current (EC) for Non-Destructive Testing (NDT) purposes is an established technique. By electronically exciting and monitoring the impedance of a coiled wire which is in close proximity to the surface of the object of interest, it is possible to rapidly detect surface and subsurface defects.
5.2 Equipment

In order to do EC inspection an operator requires an EC probe, an EC data acquisition unit and a means to display the acquired data. For the QCOALA project, as automated inspection was required, this led to the use of a system developed by EtherNDE. The display and collection of data was performed by software remotely whilst interfacing with surrounding movement systems using bespoke interfacing hardware.

Acquisition Hardware: Veritor by Ether NDE.
Acquisition Software: Veritor Automated 1.0.0.3 by Ether NDE.
Integration Hardware: A mains to 12V AC/DC converter, two microcontrollers and a motor driver.
One microcontroller provided by Ether NDE to interface Veritor Automated software with electrical signals. Another microcontroller used to interface software with other microcontroller and other robotic systems, including the linear actuator.
Actuator Hardware: 12V DC motor.

The entire EC system can be described by the block diagram illustrated by Figure 21. The interface box contains the microcontrollers and EC hardware necessary for the inspection (Figure 22), and the data collection PC has the drivers and software required for the EC inspection. The interface box also supplies the driver for the actuator (Figure 23). The actuator is installed on the attachment to the X-Y table as shown in Figure 24, and the assembled system is shown in Figure 25.

The EC system takes in a signal from the XY table controller, to then automate the movement of the actuator with the collection of data.

**Figure 21 EC Inspection system.**
Figure 22 Interface box with eddy current unit on top.

Figure 23 Interface Box with Actuator.
5.3 Approach

The approach to the EC inspection was to use the movement of the XY table and the EC system’s actuator to gather the data required whilst collecting, displaying and storing data on a laptop remotely. Two sets of data need to be acquired – 1) whilst probe is moving from air until touching (or at proximity of) the weld, 2) whilst moving across the weld. The system is reset (balanced) between the two operations.

**Figure 24** Table clamp with actuator connected to its motor driver.

**Figure 25** Probe and Vertical movement motor inspecting simulated battery weld.
Flaws to be detected

(1) Cu to Cu welds.

The Cu to Cu welds may suffer from the following flaws:

(1) Surface porosity.
(2) Sub surface porosity.
(3) Lack of fusion/penetration.

(2) Cu to Al welds:

The Cu to Al welds may suffer from the following flaws:

(1) Too much movement of the Al towards the top of the weld resulting in formation of intermetallics and cracking.
(2) Porosity (surface and sub-surface).
(3) Lack of penetration.

Method of flaw detection

Figure 26 shows the probe movements used to inspect the weld. Data collected during the first movement (1) gives an indication of the material conductivity on the surface in the immediate vicinity of the probe (eg at the start of second movement). Data from the second movement (2) is a scan along the weld and is intended to detect both surface breaking and subsurface flaws. The probe is re-balanced for the second scan.

In the first movement it is possible to tell immediately if Flaw (1) on the Cu to Al joint is likely. However it is possible that the start of the weld is different from the rest so the scan must be carried out to see if an indication of Al is obtained. When analysing the data one must be aware that the first point of the inspection may be a flaw, therefore the rest of the inspection is relative to this indication.

Flaw 1 of the Cu to Cu weld might also be indicated, in this case the deflection of the trace will be less than expected. Again once the scan is carried out then high levels of movement will indicate porosity flaws.

Detection of lack of fusion at the interface (or lack of penetration of the weld) is difficult with eddy currents because the plane of the flaws is parallel to the direction of flow of current.

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Figure 26 Inspection Plan. First movement (left), Second movement (right).
5.4 Results

Indications from Samples
Basic data showing how the metal sorting is carried out is shown in Figure 27. An example of what happens when there is surface porosity is shown in Figure 28. An example of the system detecting a weld with a high level of Al on the surface is shown in Figure 29.

Figures 30 and 31 show scans at a high frequency of a “good” and “bad” Cu welds respectively. Figures 32 and 33 show scans at a high frequency of a “good” and “bad” Cu welds respectively.

Figure 34 shows a scan across a Cu plate with slots. Figure 35 shows scan of good weld at same gain as Figure 34. Figure 36 shows a scan at same gain of a Cu to Al good weld.

![Figure 27 Basic Set-up showing indications when probe alights on Cu and Al.](image)
Figure 28 Indication when the probe alights on a pore.

Figure 29 Indications when probe alights on Al/Cu welds.
Figure 30 Scan of Good Cu weld.

Figure 31 Scans of Cu weld with porosity.
Figure 32 Scan of good Al/Cu weld.

Figure 33 Scan of bad Cu to Al weld (with intermetallic and flaws).
Figure 34 Detection of sub-surface slot in Cu plate.

Figure 35 Scan of Cu weld (at same gain as Figure 34).
5.5 Discussion

Figure 27 shows how the system can be set up to distinguish Cu and Al. This type of set up is useful because the balance is carried out in air and is therefore absolute. Where porosity occurs in a weld sample the indication is different as shown in Figure 28. It also enables an immediate distinction between a Cu to Al weld where the Al has migrated too close to the surface and there is a risk of intermetallic formation and cracking.

However it should be noted that this is only an inspection of one point of the weld. The weld must now be scanned. The parameters of the scan can be changed from those used in the initial inspection. Examples of indications from this (Figures 29-32) show that good and bad welds produce different indications basically because on a bad weld the surface is usually poorer.

For sub-surface flaws a lower frequency should be used, but at a higher gain than that used in the first scan. Figure 33 shows detection of a sub-surface slot 50% through a Cu sheet 1mm thick, and Figure 34 shows a scan of a good weld at the same gain. This shows by inference that a sub-surface flaw could be detected in the weld. The Cu to Al weld (Figure 35) will have a lower conductivity so the sub-surface inspection should therefore be more sensitive in this case.

It should also be noted that the system does not detect lack of fusion, and if only the indication amplitude exceeding a certain size were used for accept/reject then in theory the system would accept a sample with no weld. In this case a minimum indication size also needs to be used, although this is not implemented automatically yet.

5.6 Summary and conclusions

- The equipment has been built and tested to carry out a two stage inspection of the welds. The first stage gives an initial absolute indication of the weld at one location, the second a relative scan from the first location (with different parameters).
• The system has been shown to be capable of distinguishing known good and bad welds and has the potential for further refinement.

5.7 Recommendations
The acceptance criteria for the welds need to be chosen for the demonstration (and indeed for production.

6 Demonstration

6.1 Overview
The overall integrated QCOALA system for the battery application was set up at TWI’s facilities on the 30th of April 2014. Beside the technical setup, the complete system was needed to be inspected regarding the local health and security requirements.

All preparations were needed to be completed for the demonstration on the 8th of July 2014 to the QCOALA project officer and technical reviewers.

6.2 Integrated system for demonstration
The integrated system consists of the following parts, described in the paragraphs above:

• Combined pulsed q-switched green wavelength (532nm) and cw IR wavelength (1070nm) laser beams.
• Dual-wavelength processing head.
• Weld monitoring system.
• Eddy current system.
• Digital Radiography System.
• Welding Platform.

All equipment has been integrated to be remotely controlled outside the laser cell.

Figure 37 shows the integrated system for demonstration, while Figure 38 shows close up images of the individual systems that were integrated together.
Figure 37 Images of demonstration set-up.
Figure 38 Close up images of Eddy current probe a), digital radiography system b) and dual-wavelength processing head and weld monitoring system c).

The welding platform performs the welding of Cu busbars to Cu or Al terminal of the battery modules in a semi-automated way; meanwhile the WMS record a video of each weld spot and analyse it afterwards. The inspection of the welds with the EC and DR system is executed after the welding.

6.3 Laser and X-Ray safety

The used pulsed q-switched green wavelength (532nm) and cw IR wavelength (1070nm) laser beams are class 4 lasers. The definition for that class is: “Lasers in this class are high powered and capable of causing severe eye damage with short duration exposure to the direct, specularly-reflected, or diffusely-reflected beam. They are also capable of producing severe skin damage. Flammable or combustible materials may ignite if exposed to the direct beam”.
The fulfilled safety requirements for the usage of a class 4 laser include:

- Enclosed controlled area.
- Operation outside the laser cell.
- Key control.
- Special training for staff.
- Personal protective equipment.

Appropriate risk assessment and safety procedures were produced to operate within the relevant regulations.

Regarding the x-ray safety requirements, terms for the handling of the x-ray tube were approved. It was made sure that the x-ray equipment was safe to use from the outset after shipping and integration, in general compliance with the UK Ionising Radiations Regulations 1999 (IRR99). Most crucial element would be the conducting of a critical exam and testing controls in accordance with the supplier local rules and contingency plans to ensure all is well before the demonstration takes place.

All relevant safety requirements were fulfilled.

6.4 Summary and conclusions

Intelligent laser welding of Cu busbars to Cu or Al terminals of battery modules with integrated weld inspection was successfully demonstrated. All systems run as an integrated system as it was predicted.

Generally the system can be automated and therefore integrated easily in production environments.