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Multi-wave light technology enabling closed-loop in-process quality control for automotive battery assembly with remote laser welding

Pasquale Franciosa[(a)], Tianzhu Sun[(a)], Darek Ceglarek[(a)], Salvatore Gerbino[(b)], Antonio Lanzotti[(c)]
[(a)]WMG, University of Warwick, Coventry CV4 7AL, United Kingdom
[(b)]Department of Engineering, University of Campania Luigi Vanvitelli, Aversa, Italy
[(c)]Department of Industrial Engineering, University of Naples Federico II, Naples, Italy

ABSTRACT

Meeting the demands of Industry 4.0 and Digital Manufacturing requires a transformative framework for achieving crucial manufacturing goals such as zero-defect production or right-first-time development. In essence, this necessitates the development of self-sustainable manufacturing systems which can simultaneously adapt to high product variety and system responsiveness; and remain resilient by rapidly recovering from faulty stages at the minimum cost.

A Closed-Loop In-Process (CLIP) quality control framework is envisaged with the aim to correct and prevent the occurrence of quality defects, by fusing sensing techniques, data analytics and predictive engineering simulations. Although the development and integration of distributed sensors and big data management solutions, the flawless introduction of CLIP solutions is hindered specifically with respect to acquiring and providing in-process data streams at the required level of: (1) veracity (trustworthiness of the data); (2) variety (types of data generated in-process); (3) volume (amount of data generated in-process); and, (4) velocity (speed at which new data is generated in-process) as dictated by rapid introduction and evolution of coupled system requirements.

This paper illustrates the concept of the CLIP methodology in the context of assembly systems and highlights the need for a holistic approach for data gathering, monitoring and in-process control. The methodology hinges on the concept of "Multi-Wave Light Technology" and envisages the potential use of light-based technology, thereby providing an unprecedented opportunity to enable in-process control with multiple and competing requirements. The proposed research methodology is presented and validated using the development of new joining process for battery busbar assembly for electric vehicles with remote laser welding.

Keywords: Multi-wave light technology, closed-loop in-process quality control, multi-level requirements, battery busbar assembly, remote laser welding.

1. INTRODUCTION

Affected by changing market demands and introduction of new emerging technologies, manufacturing systems have undergone a number of major transitions, including mass production paradigm, driven by standardization and cost containment, to mass customization, focused on responsiveness and variety. In turn, this has brought new requirements and manufacturing has adapted with the introduction of flexible and reconfigurable systems[1]. Ever more evolving and competitive global markets with decreasing time-to-market has forced manufacturers to develop new effective self-sustainable systems which must not only adapt rapidly to high product variety, but must also be resilient to automatically recover from faulty stages at minimum cost as rapidly as possible. In essence then this necessitates producing zero-defect parts faster and cheaper[2–4]. To that end, the "zero-defect manufacturing" paradigm has opened new interesting opportunities for digital development/validation during new product and process introduction, along with integrated embedded sensors and data analytics. The last decade has seen the development of promising technologies which have boosted the amount of data generated during the manufacturing process. Today, sensors and actuators, in combination with artificial intelligence, physics-driven simulation, data visualization by virtual, augmented and/or mixed reality are sees as key enabling technologies for data gathering, monitoring and process control of manufacturing systems[5]. Traditional quality control methods, such as statistical process/quality control, though necessary for process monitoring and control, are nonetheless understood as "open-loop" approaches in the sense that they lack the capability to: (a) isolate root causes of the defect(s); (b) identify corrective actions to eliminate the isolated root causes; and, (c) develop preventive actions to avoid defect occurrence in the future. Currently, there is no effective "closed-loop" solution which links quality defect identification via in-process monitoring with root cause analysis and corrective/preventive actions.

This paper presents the concept of the Closed-Loop In-Process (CLIP) quality control methodology in the context of assembly systems and highlights the need for a holistic approach for data gathering, monitoring and in-process quality control. The methodology hinges on the concept of Multi-Wave Light Technology (MWLT) and envisages potential usage of light-based technology thereby providing an unprecedented opportunity to enable in-process control with multiple and competing quality requirements. The proposed approach is presented in the context of developing a new joining process for battery busbar assembly for electric vehicles with remote laser welding process.

2. PROPOSED METHODOLOGY

2.1 Closed-Loop In-Process (CLIP) Quality Control - overview

The CLIP approach is conceptually illustrated in Figure 1, and is based on the development and integration of 3 Key Tools (KTs): (**KT1**) Multi-Wave Light Technology; (**KT2**) Low Fidelity Artificial Intelligence; (**KT3**) High Fidelity Multi-physics Simulation. **KT2** aims at identifying critical patterns in data streams using combination of different learning paradigms, for example maximization of data coverage, maximum information rate, minimum confusion rate, maximum correctability, etc.. **KT3** allows to enhance data streams by implementing multiphysics-driven simulations (i.e., CAD/CAE/FEM). The main focus of this paper is **KT1** which will be discussed in details in the next Sections.

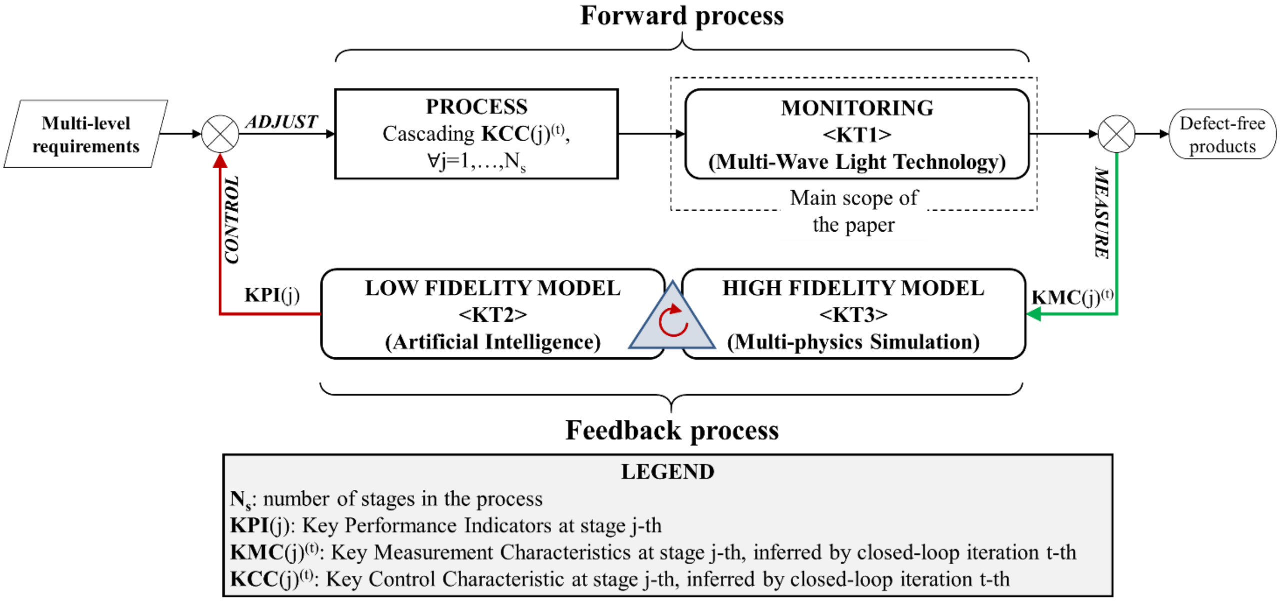


Figure 1. Proposed Closed-loop In-Process (CLIP) quality control methodology.

The formulation of the CLIP methodology must account for:

(1) **Defect**: *multi-physics* defects. Recurring defects generated and propagated in multi-stage assembly stages lead to complex cause-effect scenarios[6]. For example, in welding process one single clamp may affect mechanical deformation ("mechanical"-induced defect) as well as have impact on heat distribution ("thermal"-induced defect);

(2) **Data**: *multi-dimensionality, multi-type, multi-scale* data. With complex assembly systems the number of parameters may be very large (*multi-dimensionality*), and because of the multi-physics nature of defects data may spread from 1D signals to 3D scanned surface points (*multi-type*). Furthermore, multiple data streams may refer to different levels of granularity (*multi-scale*) in order to measure key features as related to multi-level requirements. For example, for welding process establishing the fundamental mapping between "macro-scale" joint structure and "micro-scale" grain structure is a fundamental challenge when selecting process parameters;

(3) **Model**: *multi-fidelity* models. Multiphysics-driven simulations (*high-fidelity*) are accurate but time consuming. Conversely, data-driven approaches (*low-fidelity*), based on surrogate/meta-modelling techniques, are less accurate but allows to infer correlations and dependencies among multiple and coupled parameters, thus to reduce the complexity of the design space. Models of different fidelity level are therefore necessary to leverage the benefits of both data streams. However, establishing the successful trade-off is a challenge; and,

(4) **Requirements**: *multi-level* requirements. Quality defects must comply with multiple and competing requirements. For example, in case of remote laser welding process of Battery Electric Vehicles (BEVs), the assessment of weld quality defects goes beyond the traditional joint strength. This leads on the broader spectrum to: (a) electrical requirement – lack of penetration depth control may cause insufficient contact area, which leads to voltage drop and consequent malfunction of the whole battery pack; (b) safety requirement – lack of control of penetration depth in busbar battery welding has the potential to cause cell piercing, with subsequent gas leaking and fire; (c) mechanical requirement - as dictated for example by structural welds in automotive body-in-white applications; (d) thermal requirement – thermal profiles must be controlled to avoid over-heating of the battery cells, or damage to insulators and plastic harnesses.

Key Performance Indicators (**KPIs**) are associated to cascading requirements, such as joint integrity, dimensional integrity, or cycle time. Key Measurement Characteristics (**KMCs**) are introduced to measure **KPIs**. **KMCs** can be associated to either real-time in-process data, or knowledge transfer as happening during/after design tasks. **KMCs** are either directly or indirectly mapped to **KPIs**. For example, the penetration depth during remote laser welding can be measured directly using interferometry technology, which has capability to detect the bottom of the keyhole, or by indirect signals, such as plasma emission or laser back-reflections. Key Control Characteristics (**KCCs**) are process parameters selected to deliver **KPIs**. Essential part of CLIP is to iteratively select set of **KCCs**. In this context CLIP is intended to achieve:

(1) *Robustness*: it applies when uncertainty is high - for example, missing data or input requirements -, but with fixed level of variability – for example pre-determined geometrical and dimensional tolerance. The robustness alone is typically achieved in the design stage, where pre-defined assumptions are made on input requirements. The calculated set of **KCCs** is the least sensitive to the incoming stochastic uncertainty;
(2) *Adaptability*: it applies when uncertainty is low - for example, input requirements are fully defined -, but with dynamic level of variability. Dynamic variability corresponds to evolving variability over time. Adaptability includes robustness, but not the vice-versa. In scenarios where the dynamic variability is high, the robustness, which works with pre-set parameters, does not allow to react to a broad range of configurations. This limitation is overcome by the adaptability which works with dynamically selected set **KCCs** parameters.

2.2 Multi-Wave Light Technology (MWLT)

Light and its properties are used in different engineering applications, ranging from material processing to data connectivity and communication. Light is used in advanced manufacturing processes as the power/tool to accomplish manufacturing tasks. This includes for example, forming (i.e., selective laser sintering)[7], joining (i.e., laser welding)[8], machining (i.e., laser cutting)[9], surface engineering (laser peening or dimpling)[10] and dimensional inspection and control[11,12].

Compared with traditional manufacturing process, light-based manufacturing greatly enhances the processing flexibility due to the contactless nature of light and improves the manufacturing efficiency by higher power concentration and rapid response to parameter adjustment and physical movement. Furthermore, since light-based manufacturing generally requires less consumables and post-processing procedures, it is has been proved to be also cost-effective. For example, research conducted by Ceglarek et al.[13] using Remote Laser Welding (RLW) with application to automotive body-in-white door system has proved a reduction of 30% in operational cost and 50% in cycle time, when compared to traditional riveting and resistance spot welding process. Equally important, the estimated total energy demand per product decreased by 57%. Along the lines of digital twin and digital manufacturing the interesting concept of “digital photonic production” has been presented in the laser community by Poprawe et al.[14]. In essence, digital photonic production has the capability to digitally design a component or product and fabricate it directly by additive or subtractive “photon-based” processes.

Going beyond the application of light only for fabrication as defined by the concept of digital photonic production, we envisage the possibility to use light-based technology as un-precedent opportunity to link data gathering, monitoring and in-process control. In this context we introduce the concept of “multi-wave light technology”, which must have capability for: (1) *in-process monitoring* - to collect multi-dimensional, multi-type and multi-scale data as demanded by multi-level requirements; and, (2) *in-process control* - to enable closed-loop in-process control by real-time data sharing and communication. Figure 2 shows the conceptual mapping between **KMCs** and **KPIs**, used during weld quality optimization for remote laser welding process. It could be noticed the different scales of **KPIs**, from grain structure to thermal profile, through joint structure. Although MWLT has capability for collecting multi-scale data, it is still challenged by the fact that not all data streams can be collected in-process. For example, X-ray CT scan can only be performed off-process in dedicated metrology facility. In order to overcome that challenge we propose to map **KMCs** to **KPIs** using a dual approach: (1) *training* of model mapping using off-process data; (2) *implementation* of model mapping with integrated in-process data streams. Model training and implementation is supported by the integration of **KT2** and **KT3**, as already described by Ozkat et al.[15]. The proposed approach is demonstrated in details in the next Sections using the development of a new joining process for battery busbar assembly for BEVs with RLW process.

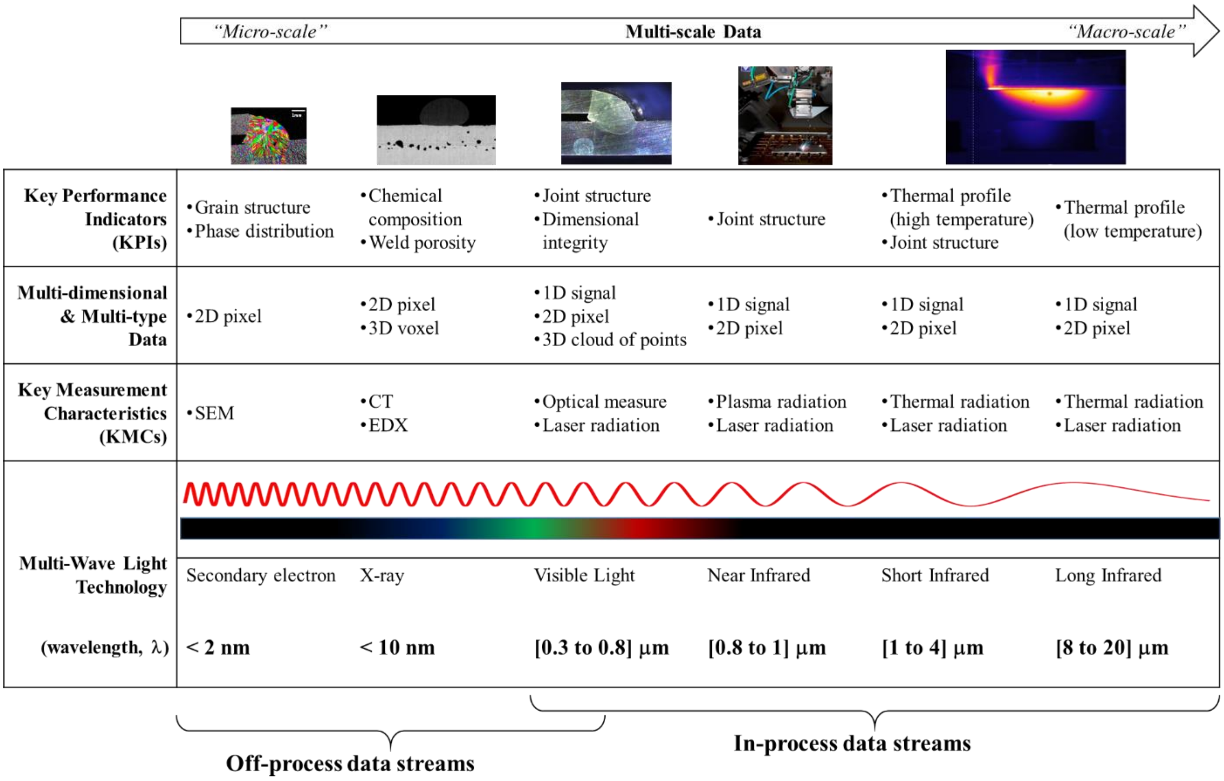


Figure 2. Multi-Wave Light Technology.
Case-in-point: weld quality optimization during remote laser welding process.

3. CASE-IN-POINT: RLW JOINING WITH APPLICATION TO BATTERY BUSBAR WELDING

3.1 Background on RLW Joining Process

RLW takes the positive features of tactile laser welding[16], such as non-contact and single-sided joining, deep weld penetration while reducing flange length, and reduced heat affected zone; and, it brings additional benefits such as increased processing speed, hence increased throughput; reduced operational cost and service, due to the reduction of auxiliary equipment such as wire feeder or shielding gas supply; and, higher process flexibility due to the capability to weld multiple/different products with the same welding head (no need for tool change-over).

The last decade has seen also the development of new inspection technology[16–19] which takes RLW to a premium position in terms of capability for in-process quality monitoring and control through light emissions. For example, sensors are distributed in the light spectrum as follows: (1) visible range (~0.3 to 0.8 μm) – joint structure and dimensional integrity measured by 1D signal, 2D pixel/image or 3D cloud of points; (2) near infrared (~0.8 to 1 μm) – joint structure measured by 1D signal or 2D pixel/image; (3) short infrared (~1 to 4 μm) - interferometer for weld penetration depth measured by 1D signal; (4) medium and long infrared (>4 μm) - thermal radiation measured by 2D pixel/image. The introduction of new stringent government regulations on CO_2 emissions has pushed manufactures to implement effective solutions to reduce vehicle weight and optimize technical performances, such as driveability, fuel consumption and safety[20]. In this context RLW is perceived as key enabling technology in car manufacturing to join lightweight aluminium structures. Recent reports by automotive OEMs[21,22] show that 50 to 60% of the car body-in-white construction is currently made of Aluminium alloys[20]. The demand of Aluminium alloys is also projected to drastically increase in the next few years due to the market push for BEVs. For instance, with the increase in battery systems and their weight, extruded Aluminium frames/chassis become highly desirable as counterbalance to reduce system cost and meet vehicle performance's targets.

3.2 Background on Quality Requirements in Battery Electric Vehicles (BEVs)

Battery pack in BEVs typically consists of tens of modules and each module is made by the joining of a batch of battery cells. Therefore, a significant amount of welding process is required to delivery electricity to and from a battery pack[23,24]. It is challenging to join such a complex battery pack system due to the diversification in geometry and requirements of each components for example tab, battery busbar and casing and the variety of joint geometry including lap joint, lap fillet joint, T-lap joint. For the purpose of lightweight design, Aluminum alloys are currently the main choice for battery pack. RLW is perceived as key enabling technology for BEV battery joining because of the capability for single side access and localized heat input[25].

Failures induced by uncontrolled weld quality have two major downside effects: (1) battery damage – uncontrolled weld penetration and position has the potential to cause cell piercing; (2) scrap of whole battery pack – only one single defective weld causes the malfunction of the whole battery pack, for example, voltage drop. Current quality control plans are mostly based on mechanical requirements, as developed in body-in-white applications – i.e., door assembly systems – to guarantee structural integrity. Though those are necessary requirements, are not sufficient for the application of battery pack where additional requirements are raised. Firstly, thermal requirement is proposed to guarantee minimum welding thermal effect to the internal battery cell and reduce the risk of fire or even explosion. Then, electrical requirement is employed to ensure adequate electrical conduction efficiency between battery modules. Scenarios with multi-level requirements poses interesting research opportunities but also challenges because multiple quality requirements may be interacting and self-conflicting with each-other. For example, a higher joint strength and electrical conductivity require a higher interface width, while a lower level of thermal effect requires less power input which generally results in a reduced interface width. In this case, the seamless mapping between multi-level requirements and selection of process parameters becomes essential for the successful deployment of CLIP system.

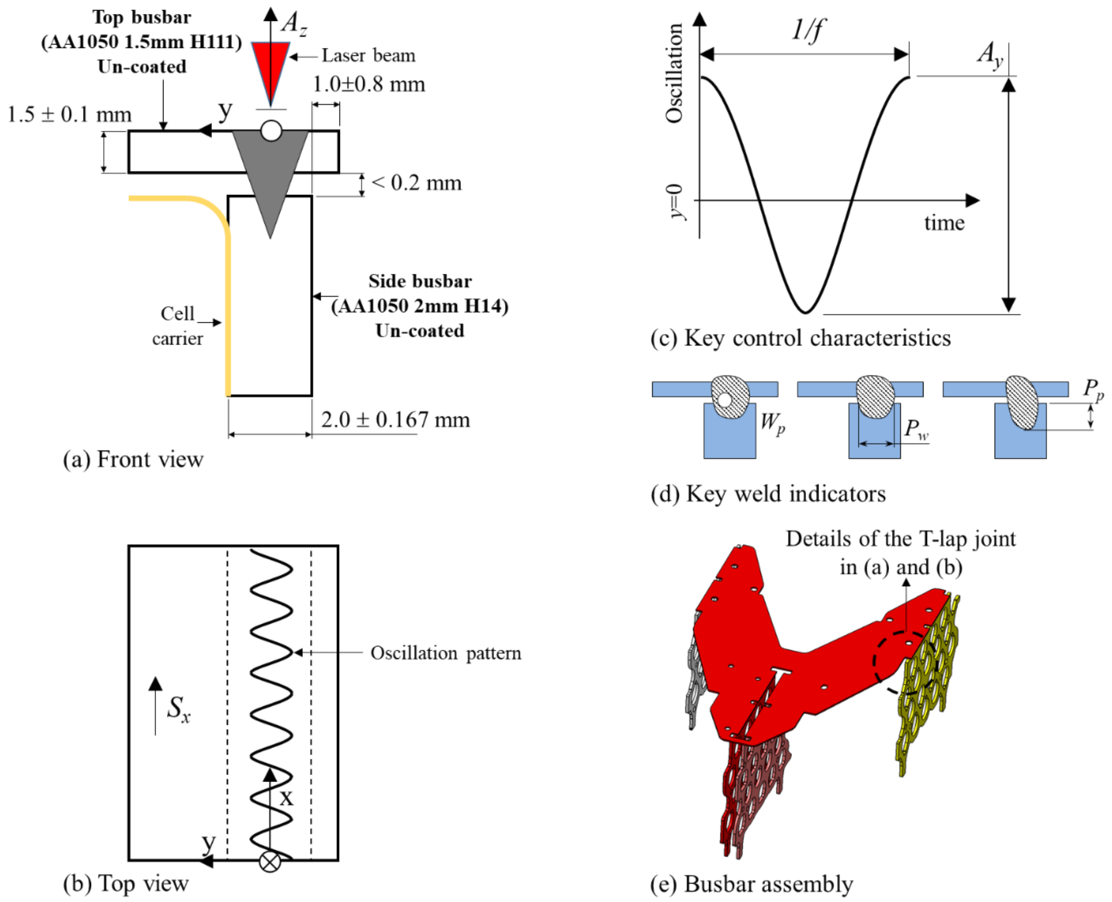


Figure 3. Schematic definition of T-lap joint configuration for battery busbar welding.

3.3 Formulation and Definition of Parameters

We aim at selecting the set of welding process parameters for pre-defined set of multi-level requirements: *electrical*, *thermal* and *mechanical integrity*. Joint structure is defined by 3 parameters: *weld porosity*, W_p, *weld penetration depth*, P_p, and *weld interface width*, P_w. Key control parameters are associated to welding parameters: (1) laser power, P_L, which is assumed constant to 2kW because of production and cost constraints on the laser generator; (2) welding speed, S_x, assumed equal to 4 m/min to comply with given cycle time assumptions; (3) oscillation amplitude, A_y, of the oscillation pattern. A_y is set to 0.3mm - higher amplitude would have led to excessive heat input and consequently fully molten pool throughout the side busbar; (4) frequency of oscillation pattern, f; (5) focal position offset, A_z; it is the distance along the beam axis between the focal point and the intersection of beam with the part being welded; it is zero when the focal point is on surface. (1) to (3) are constant, whereas (4) and (5) define **KCCs**=$\{f, A_z\}$. Figure 3 shows the schematic T-lap joint configuration along with key welding parameters. Multi-level requirements are specified as follows:

(1) Electrical integrity - electrical conductivity can be measured off-process using dedicated equipment, such as multi-meter or ohm-meter. Though this is best practice today, it does not have capability for real-time data gathering and in-process monitoring as demanded by CLIP. However, knowing that the electrical conductivity is directly proportional to the contact area, we associate it to the weld interface width, P_w. Multi-physics electrical simulations have suggested $P_w \geq 1.0$ mm to guarantee minimum electrical conductivity between top and side busbar;
(2) Thermal integrity - thermal radiation can be directly measured in-process using, for example, IR camera. The maximum temperature on the surface in contact with the cell carrier (ABS plastic) must be below 125 °C to avoid deformations or material softening; and,
(3) Mechanical integrity - joint strength is typically accessed off-process using dedicated tensile and fatigue machines. Mapping joint strength to measurable in-process parameters is a key challenge which must account for both joint structure (in-process data) and grain structure (off-process data). The minimum allowed joint strength for the single RLW stitch is assumed 70 N over 66 mm stitch length, to guarantee resistance against self-weight of the whole battery pack, and dynamic vibrations occurring during on-the-road operation of the vehicle.

3.4 Key Measurement Characteristics and Physical Principles

A 6 kW diode laser (LaserLine GmbH, Germany), with a beam parameter product of 6 mm·mrad was used. The laser beam was delivered through an optical fibre of 150 µm diameter and coupled with the WeldMaster remote welding head (Precitec GmbH, Germany), which comes with 150 mm collimating length, and 300 mm focal length. The resulting Rayleigh length is 2.8 mm. No shielding gas nor filler wire was used throughout the experiments. Samples were wiped with acetone before welding to remove surface contaminations. The material used in this case study was 1.5 mm thick AA1050-H111 (top busbar) and 2 mm thick AA1050-H14 (side busbar) rolled sheets which were machined into 38 mm × 120 mm coupons. Welds were produced in a T-lap joint configuration down the centre line of side sheet as shown Figure 3. Key MWLT measurements include:

(1) *SEM scanning* (off-process). Grain structure was characterized by electron backscatter diffraction. Samples were prepared following the polishing procedure for optical measure and a subsequent polishing with colloidal silica solution of 0.02-0.06 µm for 30 minutes. Electron backscatter diffraction (EBSD) was carried out in JEOL 7800F scanning electron microscope (SEM). The stage was manually tilted to 70 degrees relative to the axis of the electron beam and the accelerating voltage was set to 20 kV to improve signal-to-noise ratios in acquired diffraction patterns. EBSD data acquisition was performed using an AZtec HKL software platform and the resulting EBSD orientation maps, with a step size of 1.5 µm, were processed by HKL Channel 5 software.
(2) *CT scanning* (off-process). Weld porosity was detected using X-ray CT scanning, with a voxel size of 0.015mm and a scanning width of 6mm;
(3) *Optical measure* (off-process). It is used to measure the joint structure, such as weld penetration depth and weld interface width. Before measurement with optical microscope, cross-sections were mechanically polished with 9 µm, 3 µm and 1 µm MetaDi supreme solution respectively and then etched in sodium hydroxide (NaOH) solution for 2 minutes;
(4) *Laser radiation* (in-process). It is used to measure weld depth penetration. The measurement principle is based on Optical Computer Tomography (OCT) using a co-axial laser beam to the main welding beam. OCT monitors weld depth by comparing the distance to the material surface with the distance to the bottom/tip of the keyhole. The measurement accuracy is however challenged by high reflective material, such as Aluminum. Therefore, OCT is used in combination with off-process optical measures; and,

(5) *Thermal radiation* (in-process). Thermal distribution was inspected by FLIR® A655sc IR camera which was placed perpendicular to the surface of side busbar as shown in Figure 4. The IR sensor has a resolution of 640 × 480 pixels and can collect thermal radiation in the spectral range of 8-14 µm at a frequency of 50 Hz. Side busbar was covered by 0.2 mm thick Scotch® Vinyl Electrical Tape to eliminate multi-reflections from Aluminum surface and FORMEX™ GK insulator was placed behind the side busbar to avoid heat sinking.

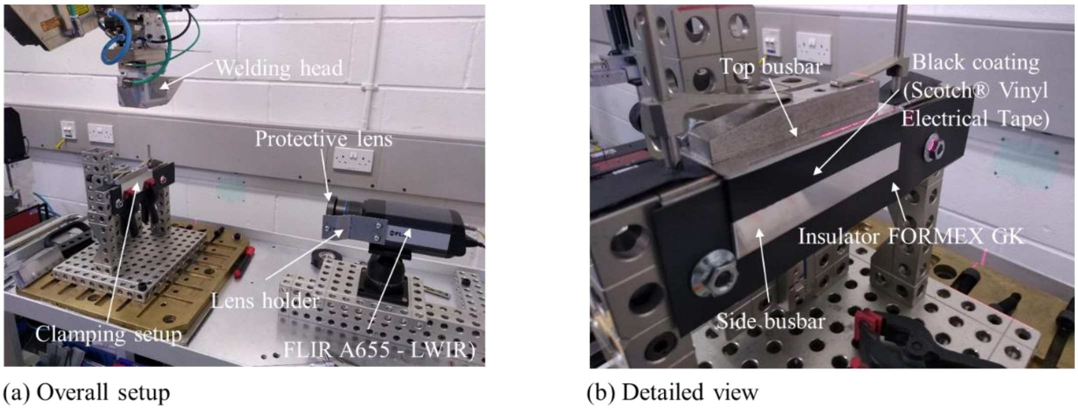


Figure 4. Experimental set-up for thermal radiation monitoring.

In order to validate the results and access the mechanical strength, tensile peel tests were performed on the entire weld joint using Instron 5985 Universal Testing System following BS EN ISO 6892-1:2016 tensile test standard. A pre-designed clamping was used to fix the top sheet and the side sheet was clamped by the instrument grip. Tensile peel loading was applied along the side sheet with a constant extension rate of 2 mm/min and the maximum loading was then extracted from the load-extension curve.

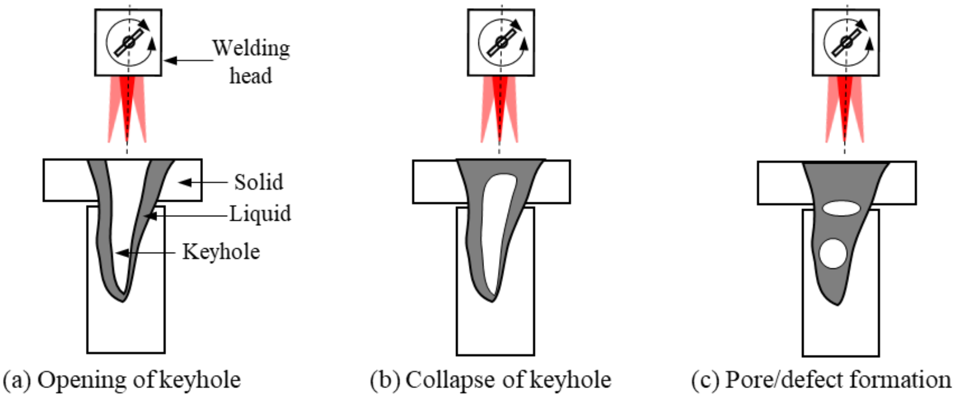


Figure 5. Schematic illustration of formation of weld defects.

The principle of formation of weld defects is conceptually shown in Figure 5. As soon as the keyhole opens up (Figure 5(a)), it starts vibrating at high frequency, typically 2 to 5 kHz. The vibration frequency is function of the material properties, surface tension and viscosity, which tend to reduce when the temperature increases. Drastic reduction of surface tension and viscosity drive towards collapse of the keyhole (Figure 5(b)) which, if not controlled correctly, leads to weld defects (Figure 5(c)), such as weld porosity and/or lack of weld interface width. Therefore, controlling the laser beam oscillation frequency and the focal position offset has clear impact of the stability of the keyhole and the temperature of the molten material.

4. <u>RESULTS AND DISCUSSION</u>

Measurements have been generated assuming that the laser beam oscillation frequency, f, has major effect on the weld porosity; whereas, the focal position offset, A_z, primarily controls the weld penetration depth and weld interface width.

Thereby, potential interactions among parameters has been neglected. The next Sections show the results obtained for each data stream.

4.1 SEM Scanning

Since the joint strength is closely dependent upon its microstructure, we aim at identifying potential correlations between grain structure, process parameters and joint strength.

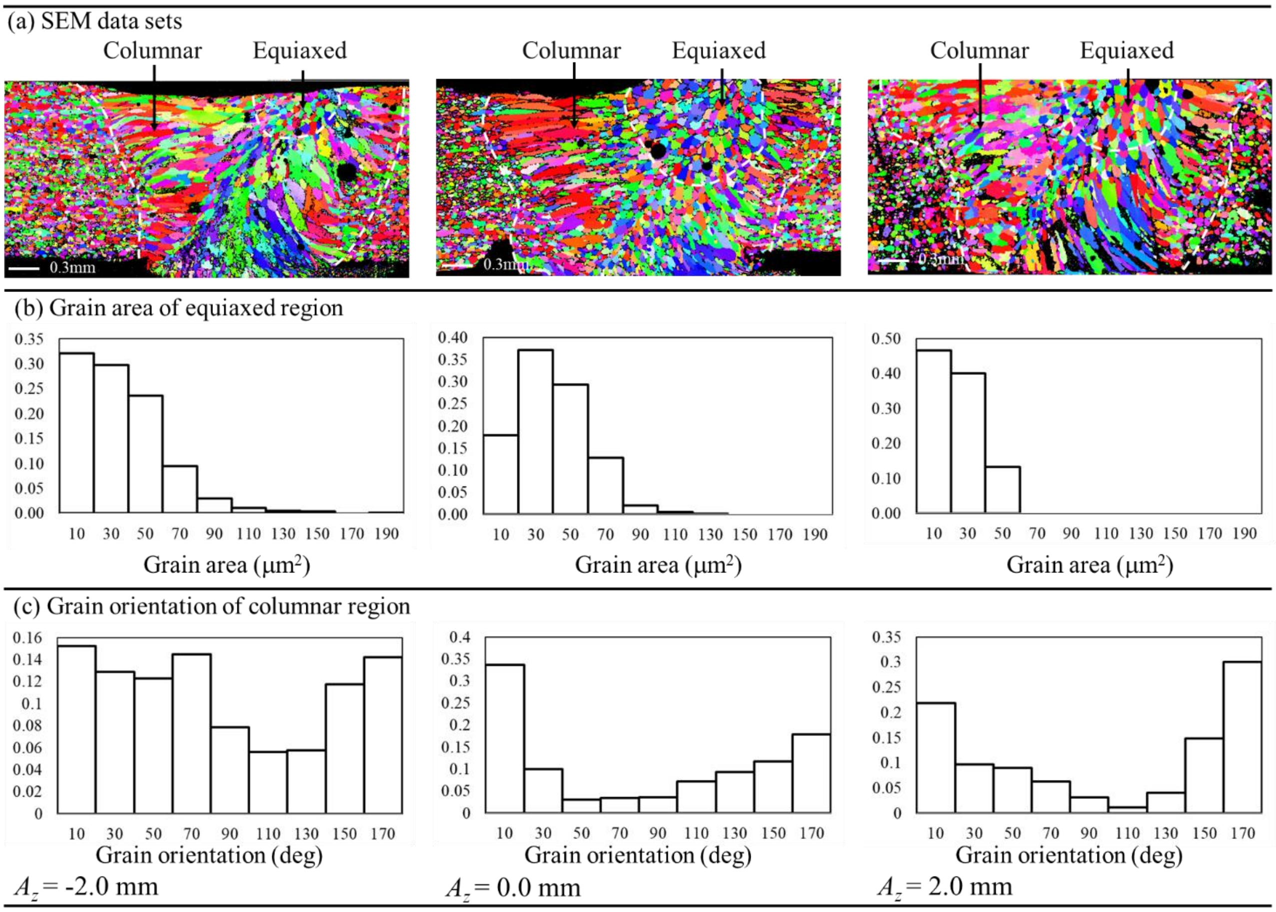


Figure 6. SEM data plotted against focal position offset, A_z. P_L = 2 kW, S_x = 4m/min, f = 200 Hz, A_y = 0.3mm.

Figure 6 shows the variation of the grain structure to changes in focal position offset, A_z. It could be noticed that small equiaxed grains were formed in the core of fusion zone while large columnar grains developed outside and elongated towards the base material due to high thermal gradient. Since material strength is closely related to the grain size according to Hall-Patch principle[26], the area fraction of equiaxed grain in the fusion zone of top busbar was analyzed and correlated to A_z. Equiaxed grains have been selected and extracted by implementing a feature detection algorithm which classifies "round" features in the SEM dataset.

4.2 CT Scanning

CT scanning has been used to measure the level of porosity in the welded seam. Figure 7(a-b) shows few representative raw images. Similarly to the SEM scanning data, pores have been identified by using a feature selection algorithm which isolates "round" features in the 2D pixel/image. The distribution of pore size has then been calculated and correlated against the beam oscillation frequency, f, and based on the results shown in Figure 7(c) it appears a weak correlation, with a p-value >5%. Therefore, it could be concluded that the effect of beam oscillation frequency on weld porosity is statistically neglectable.

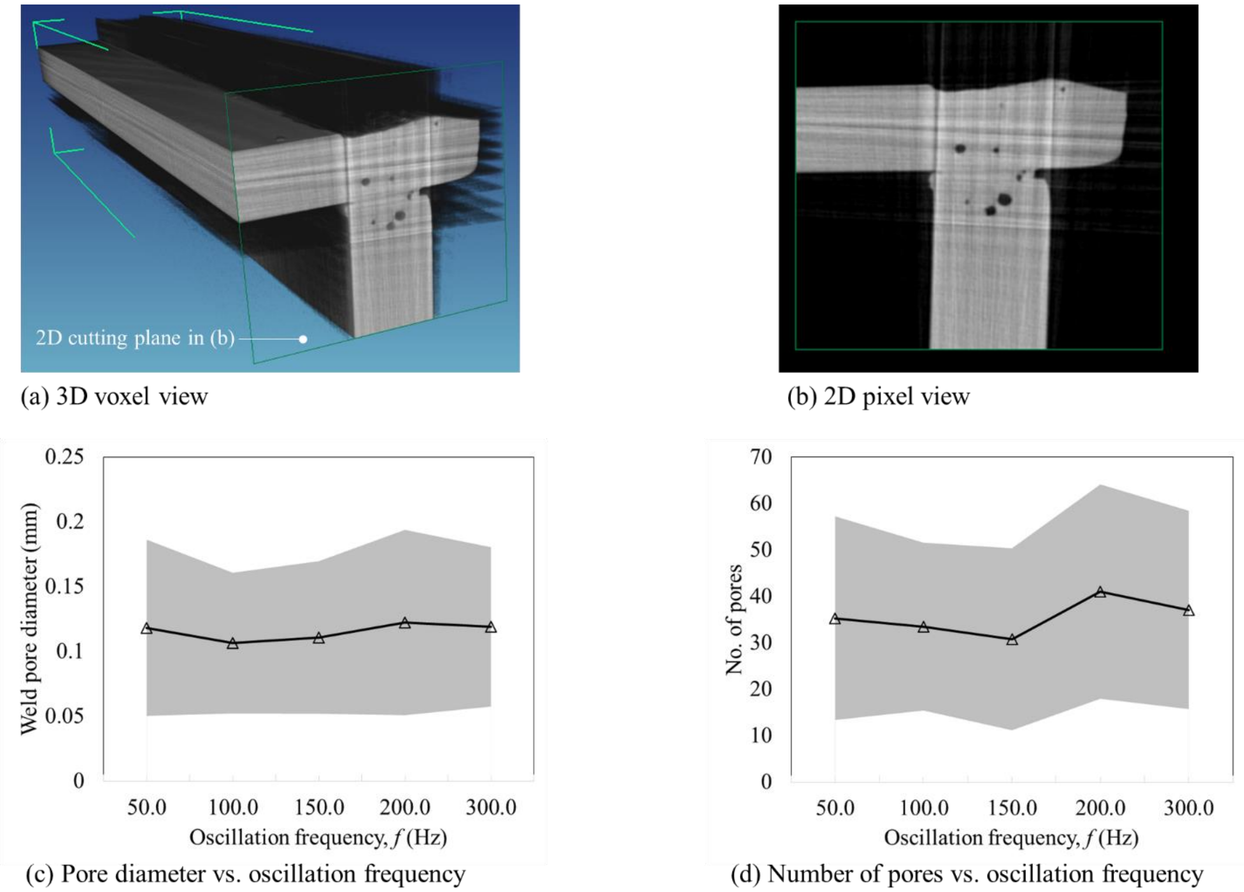


Figure 7. CT scanning data. P_L = 2 kW, S_x = 4m/min, f = 200 Hz, A_y = 0.3mm. Shaded area represents 1 standard deviation.

4.3 Optical Measure

Optical measure allows to differentiate the fusion zone from the base material. Figure 8 reports few representative cross sections. Though optical measurements provide a full representation of the weld quality they are only limited to the given cross-section area. Moreover, those measurements are performed off-process, therefore, not suitable for in-process monitoring.

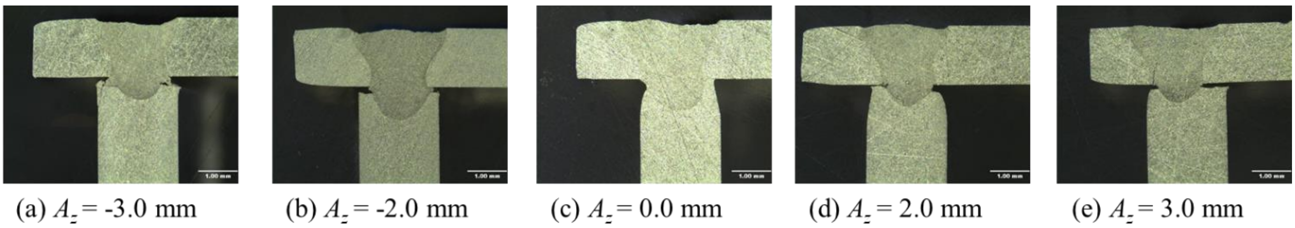


Figure 8. Optical measurements against focal position offset, A_z. P_L = 2 kW, S_x = 4m/min, f = 200 Hz, A_y = 0.3mm.

4.4 Laser Radiation

OCT technology enables in-process monitoring of weld depth penetration, therefore it overcomes the limitations of off-process optical measure. Figure 9 shows the signal data (black crosses are the raw data, while blue dots represent the filtered median signal). The scattered distribution of points is imputed to the fast vibration of the keyhole, which leads to false estimation of the true penetration due to either multi-reflections of the OCT beam or single-reflection from the side of the keyhole.

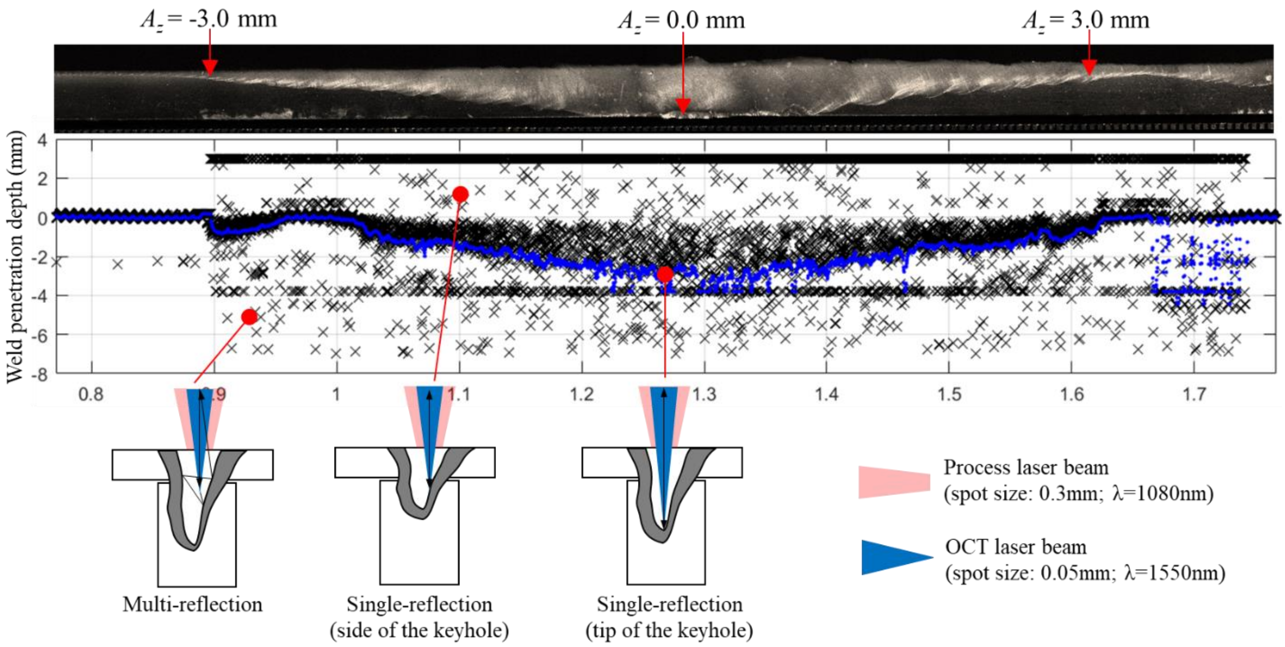
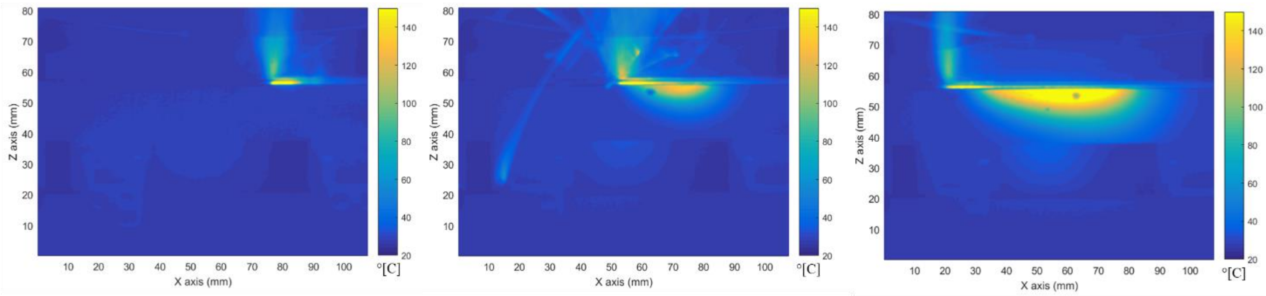


Figure 9. OCT signal. P_L = 2 kW, S_x = 4m/min, f = 200 Hz, A_y = 0.3mm.

4.5 Thermal Radiation

Surface temperature has been measured with IR camera mounted off-axis with respect to the welding head. Figure 10 shows the thermal profiles for 3 frames, A_z=-3.0, 0.0 and 3.0 mm, respectively. Image data have been smoothed using median temporal filter.



(a) Weld start - A_z = -3.0 mm (b) Weld middle - A_z = 0.0 mm (c) Weld end - A_z = 3.0 mm

Figure 10. Thermal profile. P_L = 2 kW, S_x = 4m/min, f = 200 Hz, A_y = 0.3mm, sensor capped temperature = 160 °C.

4.6 Summary of results

Figure 11 summarises the results of **KPIs** as function of focal position offset, A_z. It could be noticed that the peak of joint strength is reached (Figure 11(a)) when the A_z = 0 (focal point on the top surface of the top busbar). This results is confirmed by the area fraction of equiaxed grain (Figure 11(e)). However, the configuration A_z = 0 leads to higher level of peak temperature (Figure 11(b)) which is not desirable for the application of battery pack. Therefore, the best compromise which satisfies the multi-level requirements is reached with a slight defocus of the laser beam, either positive or negative. This result could be generalised saying that the process window which satisfies all multi-level requirements is reached at about 70% (A_z = +2 mm or Az = -2 mm) of Rayleigh length of the implemented welding head (currently, Rayleigh length = 2.8 mm). Working at those levels of defocus allows to stay in the keyhole regime, since the power density is above the 1 MW/cm^2 threshold limit, as shown in Figure 11(f).

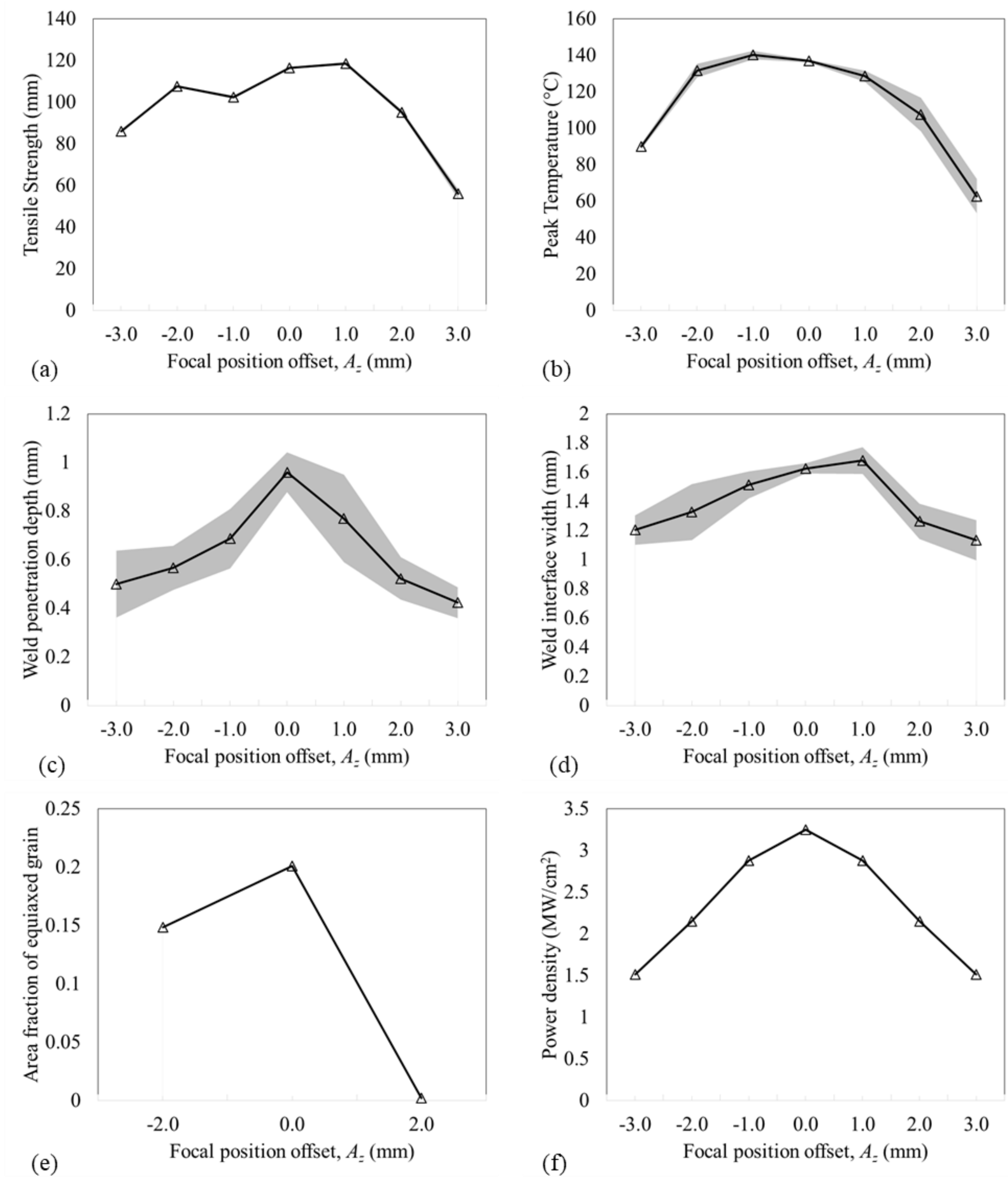


Figure 11. Distributions of KPIs as function of focal position. Shaded area represents 1 standard deviation.

5. CONCLUSIONS AND FINAL REMARKS

An essential part of the CLIP framework is to iteratively select sets of key control parameters in order to establish the "measure-control-adjust" loop, with the ultimate goal of achieving zero-defect products. It fuses in-process data, data analytics and physics-driven simulation, with the ultimate goal of diagnosing defects, if any, and correcting and preventing them from occurring in the future. The paper specifically focuses on the need for a holistic approach for data gathering, monitoring and in-process control. The methodology and its underpinning framework has been discussed in the context of "multi-wave light technology" which provides an opportunity to enable in-process control with multiple and competing requirements. The presented methodology has been demonstrated using the development of new joining process for automotive battery busbar assembly with remote laser welding process. The benefits of using MWLT are as follows:

(1) *Flexibility* - compared with traditional process, MWLT greatly enhances the processing flexibility due to the contactless nature of light and improves the manufacturing efficiency by higher power concentration and rapid response to parameter adjustment;
(2) *Scalability* - this paper has presented results in the context of automotive assembly systems. On the broader spectrum the capabilities of MWLT can be extended outside of automotive to for example aerospace systems, from single assembly station to multi-stage systems; and,
(3) *Connectivity* - wireless and laser-based communications are key elements to enable big data sharing and fast connectivity. This is perceived as key enabling technology for future smart production systems with interconnected systems and services.

Future work will be scoped to expand the vision outside of closed-loop quality control systems to smart and connected manufacturing systems using light-powered systems.

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