Materials Research Proceedings 35 (2023) 453-466 https://doi.org/10.21741/9781644902714-54

Laser welding in e-mobility: process characterization and monitoring

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Keywords Laser Welding, E-Mobility, Quality Control

Abstract. Nowadays car manufacturers have to face the challenge of electric mobility transition and it is therefore becoming an industrial priority to accomplish a large-scale battery manufacturing based on high production rates and zero-defect processes that must be obtained over a very high variety of products. The above challenges are currently examined, at the Department of Industrial Engineering of the University of Bologna, by studying and optimizing laser processes (manly cutting and welding) in case of battery fabrication and assembly. Materials investigated are manly pure copper and aluminum, processed by means of different sources, wavelengths and scanning heads. In order to reach the quality targets requested by the market, an in-process monitoring system is implemented as well as physical and data driven simulation models are under development. Finally, comparisons between the monitoring output, the keyhole simulation results, and experimental data will be carried out.

Introduction

Nowadays it is well known that the future of Mobility is Electric, ranking first among the solutions in the automotive field to address the reduction of emissions into the environment. European Parliament states that by 2035, all new cars manufactured for the EU market should produce *zero-emissions*[1]. However, switching to electric mobility represents for many companies a fundamental revamp of production technology. The electrical energy storage system is the most critical feature since the battery is the most expensive and the heaviest component inside the electric vehicle. Many companies operating in this field are adopting lithium-ion batteries because of their advantages in terms of high energy density, making them easier and faster to charge and long-lasting. There are three battery geometries for automotive applications: cylindrical, prismatic and pouch. These geometries are assembled into modules which are put together into a battery pack. The number of modules and, consequently, batteries are chosen depending on the power/energy that must be supplied by the vehicle[2].The pouch cells that contain the battery are equipped with two contact tabs made of copper and aluminum for anode and cathode. When more cells are mounted in a battery pack, electrical connections are needed between these contact tabs in order to get a serial connection of the cells[3]. Welding processes are suitable to create such contacts characterized by high strength and low electrical resistance.

In this context, laser is becoming a fundamental tool thanks to its flexibility in terms of automation and control, therefore can be easily inserted into industrial production. In particular laser-welding is widespread thanks to its production speeds and accuracy, which are the highest in the entire panorama of technologies. Automated production itself calls for a high number of welds and a wide range of differences in terms of materials, thickness and welding units involved in the process.

Lap- or butt-joint welding of dissimilar highly reflective metals, such as aluminum and copper, has been widely investigated for electrodes, as shown by Katayama et al.[4]. The latter discern thoroughly more than one-hundred papers on laser welding of thin metal sheets. It is therefore well known how to weld a proper seam in hybrid configurations. The challenge today is when it comes to high production rates and high demand of quality required by a zero-defect process. Industrial production speeds can reach up to 5-10 batteries/sec and the assembly of a single battery pack can contain up to 20000 welds [5]. It is estimated that each Gigafactory produces 6% circa of defected cells and battery modules[6]. Since most of the materials (electrodes, cell separators, electrolytes) are not fully recyclable and the whole disposal process is pricy, the quality target of the process has been set to 99.7%[6]. This highlights the central role of a monitoring system that gathers information from the process, improving the understanding of the detecting phenomena. It uses the collected data to create quality control methods and adaptive, closed loop control of the process[7]. Hence, as the number of destructive samples inspections are minimized, the implementation of a monitoring system can be seen as a product certification.

A lot of studies of online quality control have been carried out aiming at reducing or eliminating product quality defects and process errors. Nowadays monitoring systems range from simple systems using single sensors to more sophisticated systems which utilize a great deal of sensors and detection methods, as shown by Katayama et al.[8] and W. Cai et al.[9]. The latter reviewed three-hundred-ish papers describing the typical sensors used for laser welding and adaptive control: it ranges from photodiodes, visual sensor, spectrometer, acoustical sensor, pyrometer, plasma charge sensor to the application of artificial intelligence algorithms. It states that, to date, it is consolidated that the geometry of the melt pool exerts a major influence on the weld. That's why researchers are now assessing imaging as a tool in monitoring and predicting weld's quality. Moreover, machine learning models have been exploited since they are able to learn the error between the predicted value and the real value. Especially, deep learning is the present research highlight [9].

A. Bluga et al. implemented a closed-loop system based on the observation of the penetration depth of keyhole welding processes on aluminum foils. A stochastic approach was implemented for the relation between laser power and the probability to detect full penetration hole. A CNN based system called Q-eye developed by Anafocus was used to execute the algorithms for the detection of the full penetration hole. The optics units were mounted to the coaxial process window of the welding head in order to create the thermal image in the spectral range of 820 to 980 nm. A 20m cable connects the camera with the CNN control unit, which contains the interface to the laser control unit on the one hand and the PC on the other hand. The latter runs the control software which functions as the user interface. The results show that the standard deviation of the laser power was in the order of 2% [10].

Ascari et al. [11] proposed a method to ascertain the laser weld depth of battery connector tabs (Al e Cu thin foils) using *optical coherence tomography* (OCT) equipment. An adjustable ring mode (ARM) laser integrating OCT technology with two beams was exploited: one pointing at the bottom of the keyhole and the other one referring at the sample's surface. They used the "Keyhole Mapping" approach, which identifies the optimum positioning of the OCT measuring ray. Considerations on both the measurement's accuracy and the keyhole stability were made. It was demonstrated that ARM laser returns a more stable process as it reduced the fluctuations of the opening of the keyhole and it improved the measurement accuracy by the 50%.

Recently, part of the research focuses on the implementation of *deep learning* e *digital twin algorithms*. Good results were achieved by Franciosa et al. studies [12]. It presents a digital twin framework for assembly systems combining sensors with deep learning and CAE simulations. This study developed a closed-loop in-process control using a fully digital developed remote welding process for aluminum doors for e-mobility applications. It can identify the main causes of quality defects and suggest corrective actions for automatic defects mitigation.

The above studies are based mostly on deep-learning methods that can achieve only one prediction task. As laser welding is a complex phenomenon that is influenced by multiple parameters, multiple tasks have to be accomplished, as the work of Kim et al. shows [13]. Another study carried out by Franciosa et al. [14] developed a method for closed-loop in-process quality control in battery assembly lines. It is based on a holistic approach exploiting the potential use of *light-based technology*. The authors exploit both in and off-process methodologies to monitor the process: SEM scanning (off-process) to correlate grain structure with the material strength status, CT scanning (off-process), Optical measure (off-process) to evaluate weld penetration depth and weld interface width, Laser radiation (in-process) to measure weld depth penetration through OCT technology, thermal radiation (in-process) inspected with a IR camera. The closed-loop system is based on the development of a low fidelity artificial intelligence model, which identifies critical patterns in data flows that are then improved by implementing Multiphysics simulations.

Marc Seibold et al. [15] realized a process control by real-time pulse shaping where the power is adjusted in each pulse. Al-Cu thin foils were welded, and it was found out that the steps of the welding process can be captured and recognized by using photodiodes with band-pass filters.

Currently, there is little research on effective closed-loop industrial solution that can be implemented in an industrial environment: most of the technologies cited previously involved an equipment that is complicated, bulky and pricy, making them suitable just for experimental studies. Only a simple and flexible monitoring system can cope with rapid product variety in terms of materials and geometries that can be processed.

In this direction, this paper considers a low-level system which includes photodiodes sensors (Laser Welding Monitor LWM 4.0). A *low-level* system is a *ready to use* industrial system: a PD can be defined as a commercial sensor that can perform direct measurements and be easily integrated into different setups and detect different wavelengths ranges. These can be easily integrated into different setups and detect different wavelengths ranges. This kind of monitoring systems for mass production integrated in the production line nowadays do not allow a real-time modification of the process parameters, they only state, at the end of the process, if any signal values have gone out of range, which has been established previously during high-quality welding.

In literature it is described which parameters have the major influence on the process quality in laser welding but there is a consistent lack of information on the correlation between physical phenomena and sensor response. Consistently, the aim of this paper is to investigate the in-process signals measured by photodiodes and the level of correlation between the three signals in order to improve our understanding of the feedback they provide, both individually and together. The three photodiodes detect the luminous intensity of three radiations emitted over three wavelength ranges. These detectors collect plasma signal (PS), temperature signal (TS) and back-reflection signal (BS). Further details are reported in 'Process monitoring' Section. To accomplish this, experimental tests on Cu and Al thin plate were performed by varying laser power, welding speed and the length of the trace while monitoring the signals of the three photodiodes. The experimental data was evaluated offline and analyzed to evaluate the relationships between technological and signals outputs.

Materials and Method

The welding experiments were carried out using pure copper (Cu>99.6%, 0.3 mm thick), coated with a thin nickel layer in order to improve optical absorptivity of the laser radiation [16] and to avoid surface oxidation, and commercially pure aluminum AA1060 (99.4% Al, 0.25% Si e 0.35% Fe, 0.45 mm thick). The physical properties of both materials are shown in Table 1. Welds were performed on samples in a lap-joint configuration. For all the tested process parameters, both Al-Cu (aluminum on top) and Cu-Al (copper on top) configurations were examined in order to understand the importance of laser absorption and melt pool dynamics during re-solidification. For the purpose of keeping the adhesion between the two sheets during the process, a clamping device was used.

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Table 1 *Physical properties of aluminum and copper*

	Copper	Aluminum
Density [g/cm^3]	8.9	2.71
Melting temperature [°C]	1083	660
Thermal conductivity [W/ (m ·K)]	390	226
Thermal expansion coefficient [°C^{-1}]	17 ·10^-6	24 ·10^-6
Specific heat capacity [J/ (kg K)]	385	880

Methodology

Laser welding equipment and Optical Setup

Two near-infrared fiber laser sources were selected for the experiments. A single mode and a multimode laser source delivered by feeding fiber with core diameter respectively of 49 and 68 µm were used in a continuous (CW) mode for weld tests. The multimode source was a nLight Alta 3KW, while the single mode source an nLight CFL-1200. The characteristics of both laser sources and optical systems are shown in Table 2. The motions of the laser beam were achieved by a galvo scanning head for both configurations to maximize the laser speed, while the initial displacement of each weld was carried out by (ROBOT Motoman HP-20 six axes). The Precitec monitoring system, fully described in the following 'Process Monitoring' section, was mounted on the scanning head, as Fig.1 shows.

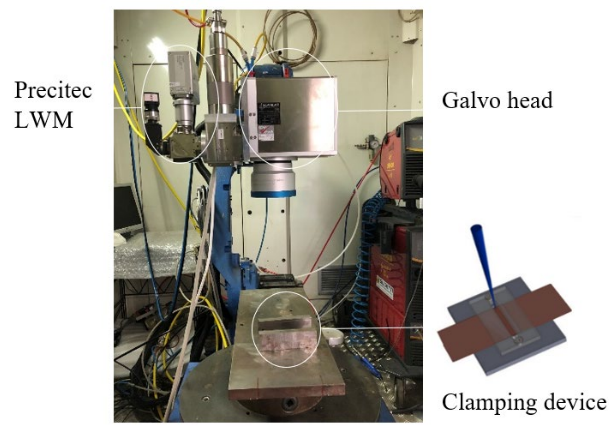

Fig. 1 *Laser system set-up. Galvo head, Precitec monitoring system and clamping device position are highlight with white circles*

The full experimental campaign is described in Table 1. After defining a feasibility window, the effects of power and welding speed on the weld bead geometry were assessed. Only the first test was conducted with the multimode laser source, while the single mode laser source was implemented in the first, the second and the third trial, with a resulting campaign of 27 weld beads for each configuration. All experiments were performed without shielding gas and without filler wire for reducing external influences on monitoring signals. In order to avoid surface contamination, samples' surface was cleaned before welding.

The two different F-Theta lenses installed in the galvo scan head lead to different spot dimensions. A 19% larger spot results from multimode laser configuration, therefore higher laser power and slower speeds are needed to get roughly the same energy density, defined as the product between power density and interaction time [J/cm3]. See Table 3.

Table 2 *Multimode and Single mode Laser source properties*

Laser source			**Optical Path**		
Specific	**Value**		**Specific**	**Value**	
	Multi mode	*Single mode*		*Multi mode*	*Single mode*
Beam's wavelength [nm]	1064	1064	Collimation length [mm]	120	120
Operative Method	CW	CW	Focal length galvo [mm]	163	420
Max Laser Power [W]	3000	1200	Fiber diameter [µm]	50	14
BPP [mm·mrad]	2	0.4	spot [µm]	68	49

In the third test, only the length of the linear weld track was increased from 48 mm to 100 mm to discern the influence of weld-path on weld-bead geometry and measured signals. A comparison was then made with the previous tests.

At the end of the experimental campaign, the welds were sectioned in the middle of the bead and were prepared for metallurgical analysis by using standard criteria for sample preparation. Cross sections of the weld joints were mounted in resin and then polished with SiC paper grit from 800 to 2500 followed by 1 µm alumina suspension. The metallurgical specimens were etched with Keller's reagent (1 ml HF, 1.5 ml HCL, 2.5 ml HNO3 and 95 ml H2O) with an etching time of 20 s for preliminary observation**.** Micrographs and weld bead measurements were taken with a ZEISS Axio Vert.AlM for a visual correspondence of the results obtained.

Table 3 *Process parameters investigated*

			Power [W]	**Speed [mm/s]**	**Weld length [mm]**
Multi mode	Test 1	Al-Cu	900-1200-1500	100-200-300	48
		Cu-Al	1200-1500-1800	100-200-300	48
Single mode	Test 2	Al-Cu	800-1000-1200	120-240-360-480	48
		Cu-Al	800-1000-1200	200-300-400-500	48
	Test 3	Al-Cu	800-1000-1200	120-240-360-480	100
		Cu-Al	800-1000-1200	200-300-400-500	100

Process monitoring

The Precitec monitoring system used (LWM 4.0; Precitec GmbH, Germany) assures non-destructive online control in real time. As Fig. 1 shows, the system is mounted on the camera flange located on the laser head. Hence, the internal optical path in the welding head is used, meaning that the sensors are always coaxially aligned to the welding spot and preserved from contamination. The system contains 3 photodiodes which detect the luminous intensity of three radiations emitted over three wavelength ranges. These detectors collect plasma signal (PS), temperature signal (TS) and back-reflection signal (BS) at a maximum sampling rate of 1kHz.

- The plasma sensor documents the UV light from the plasma plume by recording and analyzing the amplitude. The plasma control variable itself indicates the amount of metal vapor ionized during the keyhole formation process [17].

- Back-reflection is that fraction of the laser beam which is not absorbed by the material and therefore emits at the same wavelength as the laser (which emits infrared). It is consolidated that the BS is directly correlated with the keyhole geometry, thus providing information about the penetration depth [18].
- The temperature detector captures radiation in the near infrared and gives information on the thermal condition of the irradiated surface. Hence, the TS enables the identification of lack of fusion.

The system stores all the process signals in the SQL-Database, which is used to manage the Measurements and Configurations. The Control Module happens to be the core connection between the database, one or more View modules and possible external units connected by the customer. The View Module in the software guarantees a visualization of the processed signals. All the measurements were then selected and exported as .txt files, which were then given as an input for a short MATLAB script whose purpose was to graph the data and perform statistical analyses. The script was then readapted to all tests carried out in the experimental campaign, the results of which were then compared.

Results and Discussion

With the aim of developing better in-process monitoring, this paper focuses on finding correlations between the data detected by the monitoring system with the typical welding process characteristics.

Plasma and Temperature

In the first place, the welds performed with the multimode fiber source were initially analyzed and the results of test 1 were compared with each other. Al-Cu configuration was analyzed in the first place. PS and TS monitored during the laser welding process are reported in Fig. 2. If speed is fixed (v=100 mm/s), there is a linear correspondence between the two signals and power: if power steps up from 900W (blue line) to 1500W (yellow line), PS and TS increase also. It can be noticed that the trend of PS along the trace over time mirrors that of the temperature: a progressively increasing value can be noticed, which gets steeper as the laser power applied grows. For example, the increase of PS along the trace changes from 3.24% for lower power to 28% for 1500W.

This similarity between the two signals can be related to the fact that the temperature measured on the surface directly affects aluminum’s vaporization and its alloy elements leading to the opening or closing of the keyhole. This observation agrees with the findings of Franciosa [6] and I Eriksson et al. [19] who state that temperature and plasma signals are strongly correlated with Pearson’s correlation coefficient above 94%. This suggests that the plasma plume emits not only in the UV/visible spectrum but also contributes to thermal radiation in the IR, it is therefore necessary to remove the PS from the TS.

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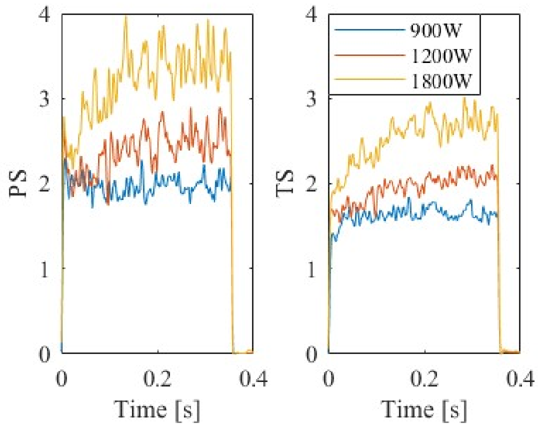
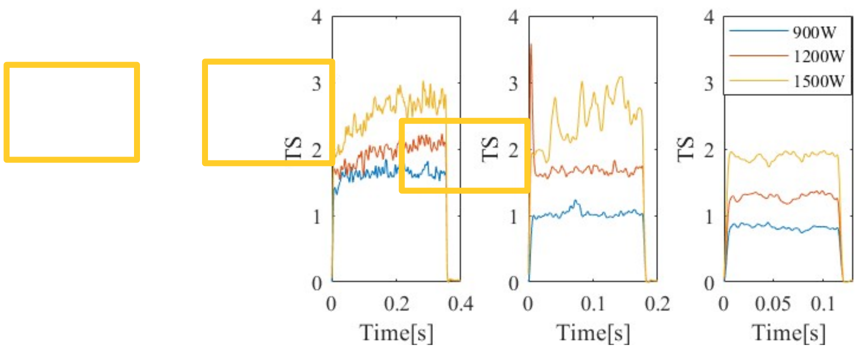


a) b)

Fig. 2 *a)Plasma and b)Temperature vs time as power ranges from 900W to 1500W for fixed velocity of 100 mm/s. Current data refers to Al-Cu configuration.*



a) b) c)

Fig. 3 *Influence of speed on the welding process in test 1: for higher values of speed which ranges from a)100mm/s b)200 mm/s to c)300 mm/s, the standard deviation of the signal decreases*

The graph in Fig. 3 describes the effect of *speed* on the process: within the process parameters window analyzed, the trend of the signals becomes more stable (less oscillating) for high-speed values up to assuming an almost constant trend (like for v=300 mm/s). From a process point of view, this data behavior could be explained as follows: for low speeds, during the laser-aluminum interaction, the component increases its temperature moment by moment since not all the heat can be dissipated by conduction. Therefore, it is logical to think that, by heating continuously, the characteristics of the joint vary from the beginning to the end of the weld bead. This problem of heat accumulation during welding is emphasized for low speeds that lead to a longer interaction time and the amount of heat absorbed by the material increases with it. In the graphs in Fig. 3 this behavior is very evident: as the speed increases from 100 mm/s (Fig. 3 a) to 300 mm/s (Fig.3 c) the signals are much less oscillating and more centered on the average value, which, presumably, is equivalent to a more homogeneous, sound weld bead along the track. To sum up, BS and TS standard deviation (T_{std} ,P_{std}) increases as laser power increases and decreases for higher speeds, which comes to a higher energy density on the material. This feature is found to be more relevant for the Cu-Al configuration, hence the Fig.4 is reported. This means that the more energy density is applied, the more the signal oscillates, hence the more unstable the keyhole gets.

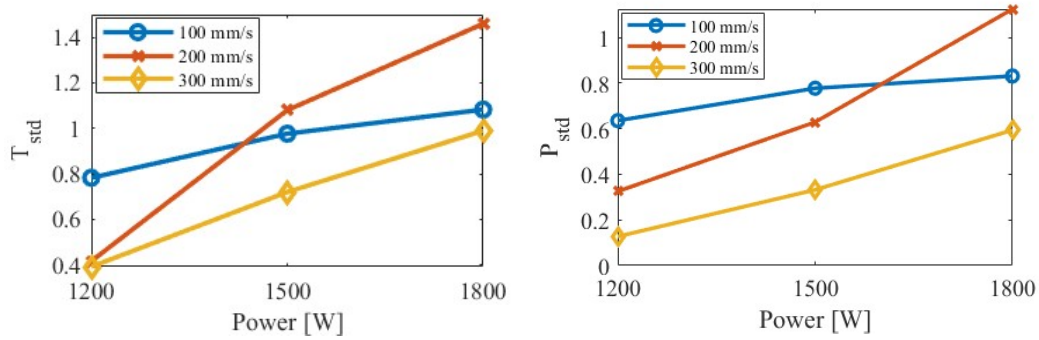


Fig. 4: *Temperature and Plasma signals standard deviation for test 1 Cu-Al. As laser power increases and speed is diminished, an increasing trend can be noticed, leading to keyhole instability.*

The increasing linear relationship is consistent not only for T_{std} and P_{std}, but also for PS. As previously anticipated, the mean value of PS (P_m) and TS (T_m) was calculated for every test over the whole weld bead when a multimode laser source was exploited. The resulting values are plotted in Fig 5, both for Al-Cu and Cu-Al configuration. There is clear evidence of a linear relationship between power and monitoring signals. Similar trend was identified also for weld-bead width. The micrographs reported in Fig.6 point out the different characteristics of the weld bead morphology of Al-Cu and Cu-Al configurations. In Al-Cu the laser beam interacts with aluminum, and its weld bead tends to be larger at the top and narrower at the bottom, while if the first interaction is with the copper, the situation is the opposite. This behavior is due to the different physical properties of the two metals involved in the process, in terms of heat conduction coefficient and melting temperature (see Table 1). When the aluminum is at the top side, the laser beam melts, at first, the material that has the lower temperature melting point and then the copper that is situated at the interface between the two sheets. Copper has a much higher melting point and a higher thermal conductivity than aluminum, that’s why it melts to a much lower extent.

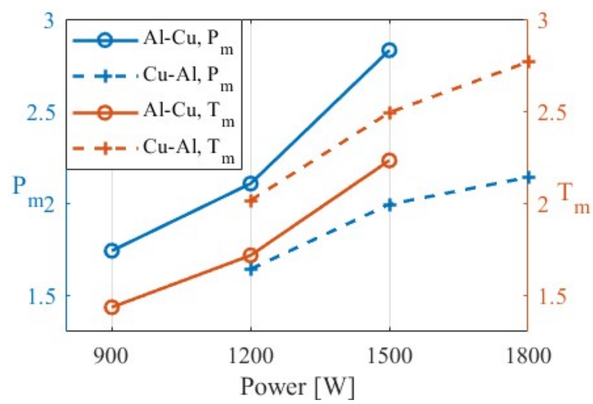


Fig. 5 *Mean values of PS when a multimode source is exploited and speed is fixed at 200mm/s for both Al-Cu and Cu-Al configurations.*

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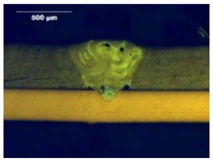
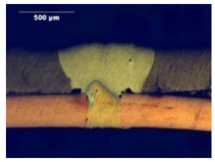
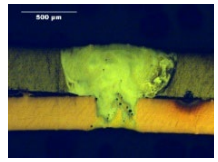
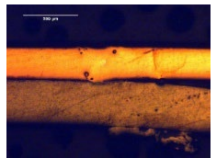
P[W]	900	1200	1500	1800
Al-Cu				-
Weld Width [μm]	687	868	1054	-
Cu-Al	-			
Weld Width [μm]	-	170	495	590

Fig. 6 *Corresponding micrographs and weld bead width taken at the middle of trace.*

When copper is at the top side, heat is transferred very quickly at the interface between the sheets because of the higher melting temperature, if compared to aluminum. The latter melts abruptly and, if the energy is excessive, tends to favor a complete penetration of the specimen [20].

Another thing that can be noticed is that the average amount of metallic vapor produced during the interaction between the laser beam and the aluminum is way higher than that found for welding the copper first: in

Fig. 5 Al-Cu P_m curve assumes plasma values ranging in an interval that is higher than the Cu-Al P_m. This happens because aluminum has a lower phase transition temperature than copper and therefore vaporizes before. The width variation can then be monitored by the signal values of either plasma or thermal radiation during welding.

It is consequently confirmed that the control of the laser power based on thermal radiation values can minimize the variation in the bead width.

Back-Reflection

In the following paragraph BS is analyzed in test 1 Al-Cu. A comparison is then made with the data obtained in test 3 to comment the influence of the welding length. For tests 2 and 3 similar results were obtained, therefore the discussion can be extended for all Al-Cu tests. For the Cu-Al configuration such a marked trend was not evident: as the power and speed change, the signals mean values were almost steady. In general, it is well known that material absorptivity decreases with an increase in the welding speed [4]. As the welding speed increases, the molten pool becomes smaller, and the melt zone in front of the keyhole is also narrower (or thinner). That is, at higher welding speeds, a part of the laser beam is irradiated on the thin melt zone and solid metal surface; consequently, the laser back reflection increases, and the ratio of a laser beam absorbed into the keyhole decreases. The histogram in Fig. 7 testimony the latter consideration: increasing speed, the back reflection signal increases.

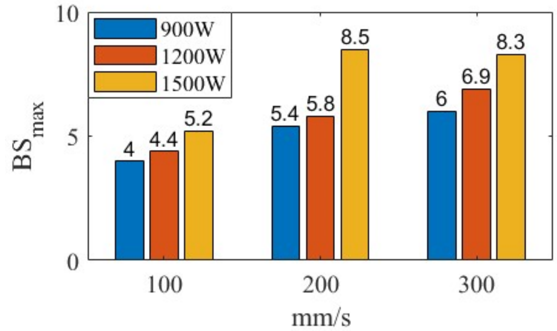


Fig. *7 Peak values of the Back reflection-time signal at varying power and laser speed for test 1 Al-Cu. It can be noticed that as the speed increases also BS increases as a smaller amount of laser beam is absorbed because of the narrower weld bead formed.*

The BS itself is characterized by a fast peak near the central area followed by a fast drop, decreasing towards the end of the track. The bell-shaped pattern is probably due to the fact that the sensor, remaining integral with the laser head during the whole welding process (as a galvo head is expected to work), is able to collect all the radiations only in the configuration in which the laser head is positioned at the center of the trace and the beam is perpendicular to the surface. In all other welding positions, the inclination of the laser beam towards the surface increases and makes a good percentage of the light radiation going out from the sensor's reading range. For this reason, to make comparison analysis, the maximum value is considered, which is the peak point of the hilly trend. In support of this assumption, test 3 was carried out, where only the length of the track was changed. It was found that the bell-shaped trend is more marked: the sensor will receive very weak light radiation from the points furthest from the center of the weld bead because of the greater inclination. By making the weld bead longer, the surface temperature of the aluminum and the plasma detected decreases, if compared with the previous tests.

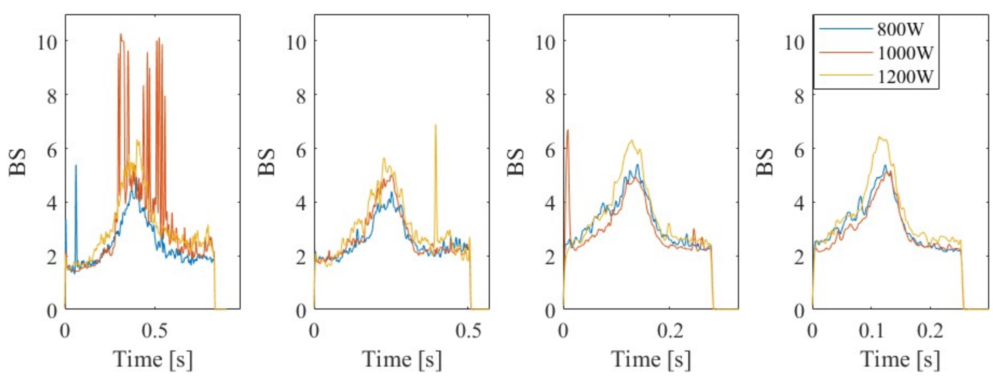


Fig. 8 *Hilly trend of the BS-time at varying power and speed that ranges from 120 mm/s (to the left) to 480 mm/s (on the right) for test 3. The bell-shaped trend in longer weld beads is more marked: the sensor will receive very weak light radiation from the points furthest from the center of the weld bead because of the greater inclination of the laser beam.*

Looking at test 1, a comparison between BS collected during Al-Cu and Cu-Al configuration was carried out. It is clear that BS on copper is always greater because it has a lower absorption coefficient than aluminum (for the percentage increase look at Table 4).

***Table 4** Percentage increase values from Al-Cu to Cu-Al configuration in the operating window considered*

Power [W] ↓ / Speed [mm/s] →			
	106%	165%	170%
	65%	154%	133%
	133%	82%	96%

Statistical Analysis

In order to hold together the results from the whole experimental campaign, the spot dimension has to be taken into account as single and multimode sources were exploited. For every set of parameters, the mean value and the standard deviation were calculated for each weld bead and plotted against energy density.

As Fig. 9 states, TS can be modelled with a linear regression with a good accuracy. In fact, the statistical analysis obtained with MATLAB shows a very low p-value and an R^2 very close to unity (R^2 =90%), suggesting that the linear model used for temperature variable interpolates the data very well. However, this correlation is not true for back reflection and plasma variables, whose intensity depends on the laser source exploited for the experiment, as Fig. 10 points out. Hence, two different models must be implemented in order to describe the welding process carried out with two different sources. In order to monitor the stability of the process, the standard deviation of plasma (PS_{std}), temperature (TS_{std}) and back-reflection (B_{std}) versus Energy density Es were plotted. In this account, some considerations were raised: the TS_{std} graph in Fig.11a) shows clearly three patterns for both multi and single mode sources. These linear patterns were analyzed, especially for the multimode tests where it was more evident that the separate trends, with three points each, were characterized by equal speed. The histogram in Fig. 11b) shows how the TS_{std}, which is directly correlated to process stability, depends more on power than speed: keeping the process at a constant speed, it becomes more instable as the power increases, and not vice versa. Consequently, it is possible to suggest changing the *power* as the variable input in the closed-loop system if any signal exceeds the threshold.

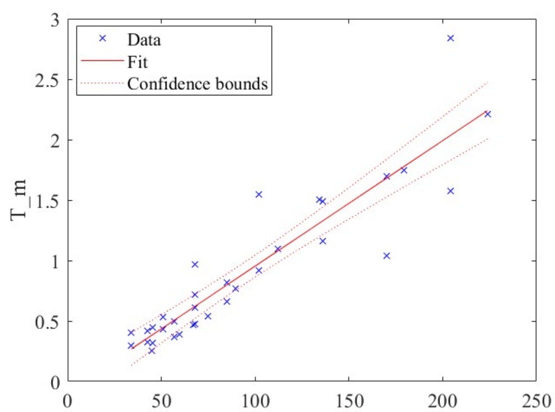


***Fig. 9** Linear regression for TS with a R^2 = 90%*

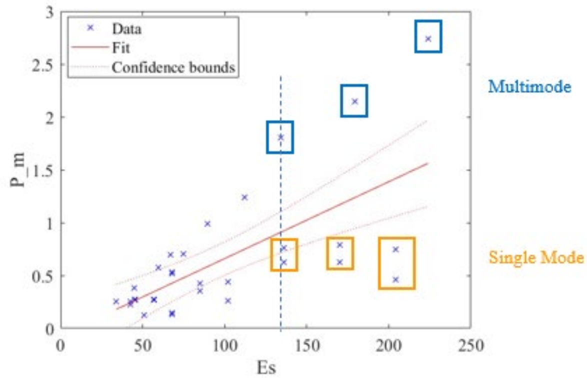


Fig. 10 *Plasma values for both single mode and multimode sources. If a multimode source is exploited, the intensity of plasma radiation recorded grows with those of the power density (E_s). On the other hand, if a single source is exploited, the variation of PS from the mean value is not significant*

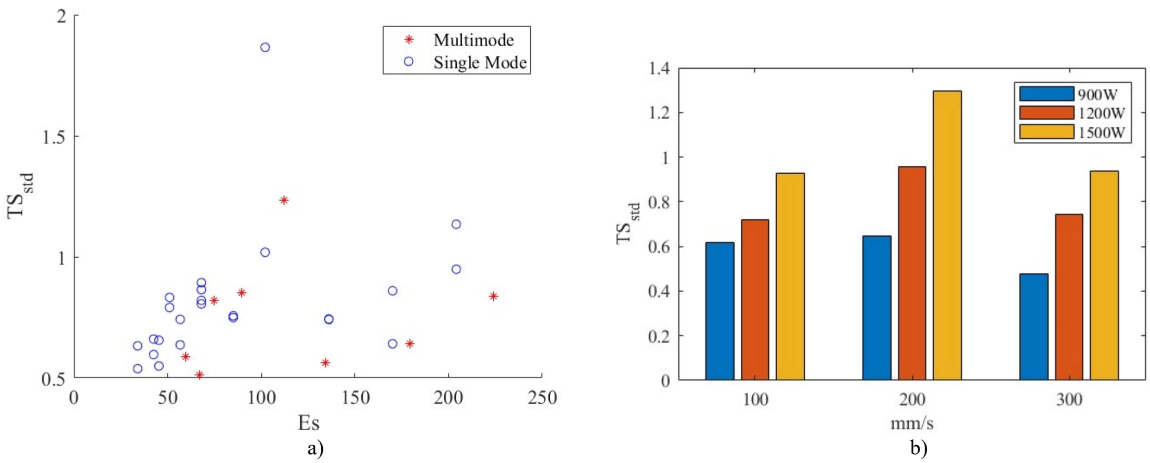


Fig. 11 *a) TS_{std} against energy density Es for single and multimode sources. Three linear trends can be noticed with three scatter points each in every of which the speed is kept constant and the Power is increased. This consideration is validated by the histography in b) where for every speed, for an increased value of power, the process becomes more instable (standard deviation values increase).*

The same studies were made on Cu-Al configurations and the same results were observed.

Conclusions and future work

To sum up, the following results were obtained:

- Signal standard deviation or signal variance data can be used to improve the accuracy of laser welding monitoring devices, as Olsson states in his work[21].
- The plasma trend mirrors that of the temperature: the temperature directly influences the vaporization of the aluminum and its alloying elements leading to the opening or closing of the keyhole. This observation agrees with the findings of Franciosa [6] and I Eriksson et al. [19] who state that temperature and plasma signals are strongly correlated with Pearson's correlation coefficient above 94%, and thus a similar signal is delivered. This suggests that the plasma plume emits not only in the UV/visible spectrum but also contributes to thermal radiation in the IR.

- There is an increasing linear relationship between plasma and power for the multimode source tests, a decreasing linear trend for the single mode ones. Observing the micrographs, the variation of the weld seam's width seems to follow the same tendency varying the power with the other parameters in play being equal.
- With the same power density as E_s the plasma values obtained in the multimode tests are greater than those obtained for the single mode tests for the Al-Cu configuration. This increased value is probably due to the greater width of the bead (the sensor detects more radiation).
- Within the window of process parameters analyzed, if high speeds were set, the trend of the signals stabilizes (less oscillating) until it assumes an almost constant trend. Hence, the standard deviation of the signal disclosed an explicit correlation with the stability of the process. This consideration is valid within the considered operative window. It is possible that the signal turns to be unstable if the speed is increased more.
- The back-reflection varies with a bell-shaped trend: the sensor is able to detect all radiations only in the configuration in which the laser head is located in the center of the trace and the light beam is perpendicular to the surface. In all other positions, a good percentage of the light radiation goes out of the reading range of the sensor. This behavior only affects the signals but not the weld quality itself [6].
- The average amount of metal vapor produced during the interaction between the laser beam and aluminum is much higher than that detected for copper welding because aluminum has lower phase transition temperatures than copper and therefore vaporizes first.
- The back reflection on copper is always greater because it has a lower absorption coefficient than aluminum.
- The power is expected to be the most influent variable for the closed-loop monitoring system.

Based on these observations, future technological implementations might follow:

- It is conceptually possible to exploit plasma as an input to regulate the power with a feedback control to keep the temperatures constant during the process.
- The analysis of the plasma vs energy density trend confirms that any threshold value you want to define for the control of the seam strictly depends on the laser source used.
- If the consideration that was made on the back-reflection signal is true, it therefore makes this signal of little use for the analysis of the single trace but can only be evaluated in a comparative way with a pre-acquired signal on a bead, whose properties are considered acceptable.
- The takeaway from the comparison between Al-Cu and Cu-Al configurations is that any threshold value for the bead control strictly depends on the first material irradiated.

During the analysis of the dataset, the width of the bead emerged to be a relevant parameter for the control of the opening/closing of the keyhole. This observation led us to consider the implementation of a camera system on the laser head capable of measuring the variations in shape and size of the keyhole as a possible evolution of this research. In this way, the correlation between the data detected by the sensors and the welding behavior observed by the high-speed imaging shall provide greater precision in welding control, guaranteeing the required quality. It is essential to have a larger dataset available in order to apply Machine Learning and Artificial Intelligence techniques to be able to link the behavior of one or more sensors and match it to a specific real defect and ultimately, prevent it through feedback control. That is to say, humanizing the whole

Materials Research Proceedings 35 (2023) 453-466 https://doi.org/10.21741/9781644902714-54

laser welding monitoring process (acquiring signals, analyze them and making monitoring targets) [9].

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