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Dynamic laser beam shaping for laser aluminium welding in e-mobility applications

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Abstract

High demanding novel laser welding applications are currently encountered in e-mobility sector such as overlap joint of thin aluminium alloys without full penetration for battery coolers and battery boxes. In this work, high dynamic laser profiles enabled by unique CIVAN proprietary Coherent Beam Combining (CBC) and Optical Phase Array (OPA) technologies are explored. Experimental investigation of overlap welding of 3003 aluminium alloy plates of 0.8mm thickness at speeds over 10m/min and the study of main process parameters, various beam shapes and oscillation patterns at high frequency up to MHz are undertaken. Effects of laser beam intensity profiles, oscillation frequencies in resulting seam shapes are presented. Process optimization is carried out in terms of weld seam geometry width and depth of penetration avoiding defects as porous, cracks and voids in the interface. Quality of weld joints is evaluated by cross sections macrographs and metallographic examination.

Keywords: emobility, aluminium, welding, shaping, oscillation

1. Introduction

Current efforts in novel laser welding applications development mainly target e-mobility and automotive sectors, as they are continuously increasing the use of aluminium alloys in manufacturing. Emerging applications such as welding of battery coolers and boxes are examples of niches where laser-based processing can have an edge over other manufacturing methods due to its flexibility, scalability and weight reduction by using new developments of Al alloys.

This paper reports an experimental study of laser lap welding configuration of aluminium alloys sheets in key-hole welding mode. CIVAN's Coherent Beam Combining (CBC) and Optical Phased Array (OPA) technologies featuring dynamic shaping and fast oscillation up to MHz rates integrated in one laser has been used for development of this high-demanding laser welding applications [1].

For this type of application, acceptance and validation criteria for the welded seam are: defined set of seam geometry characteristics (interface width and partial penetration depth) and minimisation of defects such as porous, cracks and voids in the interface (defined by manufacturer and dedicated relevant standard [2]).

Adequate laser welding results (i.e. stable weld seam without defects such as porosity, voids, cracks, etc.) have been found in recent studies for analogous applications at speeds up to 100mm/s=6 m/min by employing current state of the art technologies of beam shaping (tailoring beam irradiance profile) together with fast oscillation and wobbling created by laser optical heads.

Although laser oscillation, also known as stir welding, is applied to various metallic systems, it is especially appropriate to laser welding of aluminium alloys, because liquid aluminium possesses significantly less surface tension and viscosity than

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most common metal alloys, which results in greater fluidity of the molten pool and keyhole instability [3]

Mechanisms of melt pool dynamics by the stirring effect on laser keyhole and that beam oscillation stabilizes the process and improves weld morphology have been demonstrated and applied to aluminium welding [4],[5]

Fiber laser beam sources in connection with a high frequent beam oscillation have been used to join metallic material combinations, which had been conventionally non-laser weldable [6] This high oscillation has been also demonstrated useful for high penetration welding [7] other aluminium alloys improving its microstructure. [8] and mechanical properties of the weld [9]

Even though Gaussian and top-hat beam profiles are suitable for most laser welding applications, for certain cases other beam distributions can be favored in terms of weld quality or performance [10]. One method to generate a tailored beam shape is diffractive optical elements. This tailoring energy distributions during laser welding using DOEs have been investigated for other e-mobility applications. [11], [12]

In recent years, laser oscillation welding and beam shaping are main topics on laser welding developments as novel laser sources and new systems have recently entered into laser industrial solutions market. Recent studies have shown that a fiber laser beam shape consisting of a central laser spot surrounded by an annulus or 'donut' can substantially improve the stability of a keyhole weld. [13]. [14]

Beam shaping can also be achieved by adding optical elements (e.g. DOEs or MPLCs) to standard lasers or by special lasers with integrated shaping capabilities (i.e. laser based on double core fiber principle). Existing constraints for these are mainly the few quasi-static beam profiles (e.g. ring, flat top, gaussian) that can be obtained.

Fast beam oscillation is produced by galvo-scanners moving transversally to weld direction. This movement impacts positively on the seam geometry and on the minimisation of defects. However, wobble speed for this technology is typically limited to 2-4 kHz range.

CIVAN has developed a novel technology which allows unprecedented versatility and flexibility in laser material processing. Relying on Coherent Beam Combining (CBC) and Optical Phase Array (OPA) technologies, CIVAN's OPA6 laser is able to dynamically tailor beam parameters to the required application.

With CBC technology, multiple laser channels are electro-optically controlled to combine or interact with each other. OPA6 laser stands for optical phase array configuration in a matrix which allows movement and power distribution of 1:6 ratio from the main central lobe. CIVAN's OPA series is a high power single mode laser capable of dynamic beam shaping and focusing, oscillation in free form patterns and power modulation.

In this paper, OPA6 laser is used to investigate the effects of combining high speed beam shaping and oscillation on overlap welding of aluminium AA3003 sheets. It demonstrates that the combination of further increasing the speed of laser spot oscillation and the use of tailored beam shapes improve processing speed and the overall quality of the seams.

2. Experimental setup

Welding application tests were carried out at CIVAN's applications facilities. The experimental laser workstation (Fig. 1.) consists of a CW OPA6 laser (wavelength = 1064 nm, max. power = 14 kW, spot size = 600 µm and $M^2 < 1.1$), focusing optics (f = 1,5 m), HR mirror to guide the beam onto the work piece and a monitoring port for power or beam profile measurements.

The work piece is placed on an CNC-based XY-positioning system (500 mm x 250 mm working range at 20 m/min max. speed). A clamping tooling is used to secure the parts to be welded.

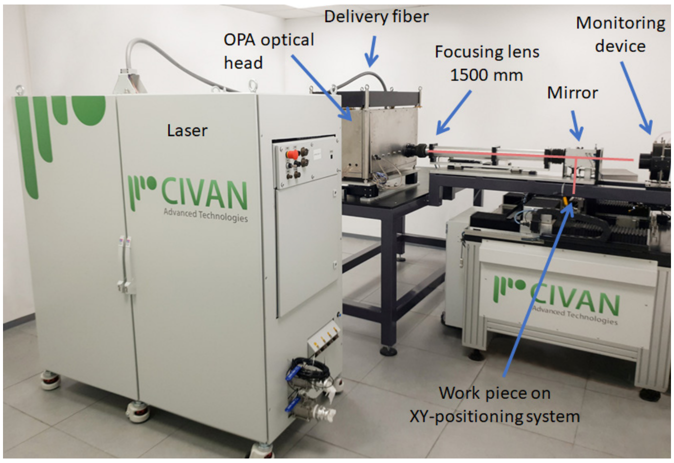
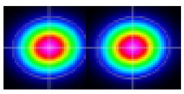
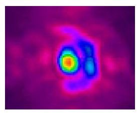
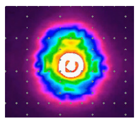
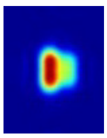
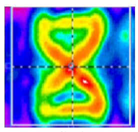
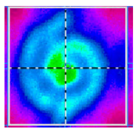


Fig. 1 Laser welding workstation

Pairs of AA3003 sheets of 50x100mm and 0.8 mm thick were clamped on both sides of the weld line along its entire length.

Flexibility of the laser OPA6 system allows the investigation of these different irradiances profiles. Dimensions XY of the square that circumscribes these geometries are in the range of 0.3-0.5mm. Beam shapes depicted in Table 1 were investigated

Table 1 Beam shapes tested for AA3003 partial penetration lap welding

		
2 spots	C + spot	Circle + spot
		
Pyramid	Infinity	Spiral

Parameters set definition

Conventional laser welding applications are mainly defined by laser power and process speed, also referred as welding speed or feed rate as a main parameter set: For oscillation welding, it is also important to investigate the effect of amplitude, frequency and pattern of beam oscillation.

Unique features of possible irradiance profile shapes created by CBC at OPA technologies in CIVAN laser requires new parameter defecting for application development, that captures how this beam shape is spatially and temporally generated.

In this laser system, each shape consists of certain number of points that can be shifted spatially in a 20ns refreshing time. Therefore, following parameters can be defined for each of the shapes: number of points, time on point (multiple of 20ns). Multiplication of these 2 parameters gives total shape time. The range in which this shape can be adjusted is quite wide as usual shapes are conformed by 10-50points. The inverse is what we call "shape frequency" and this is the main parameter that is investigated process tests.

Thus, each shape can be refreshed with a certain frequency. for a certain shape and depending on temporal reconstruction of that shape, we can explore a wide range of shape frequencies ranging typically from 1kHz-1MHz. This is depicted in schematics below considering the example of the infinity shape and by the definition of two new process parameters:

- -number of shapes per mm, ratio between the shape frequency and welding/feed rate speed. (Eq.1)
- -the overlap length of the shape is calculated based on previous and the shape width in the welding direction. (Eq.2)

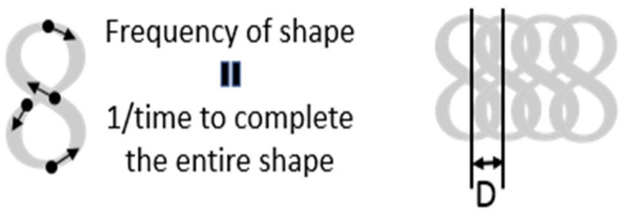


Fig. 2 Illustration on shape frequency and shape overlap

$$n = \frac{F_S}{v_L} \quad (1)$$

n= number of shapes per mm
F_S=Shape Frequency (Hz)
V_L= welding speed (mm/s)

$$D = \frac{W * n - 1}{n - 1} \quad (2)$$

D= overlap
W=width of the shape

Characterization and quality criteria

Metallographic examination was undertaken to measure the cross-sectional size and shape of the welded spot. Particularly these geometrical dimensions: seam width at the upper plate: interface width at the bottom plate (effective weld section) and penetration depth (measured from interface). This results in optimum weld seam specification based on optimum bonding cross section for maximum strength Quality criteria of the application is completed by the minimization of following defects: porous, cracks and voids in the interfaces

Scanning Electron Microscope (SEM) and Energy-dispersive X-ray spectroscopy (EDX) were carried out as analytical methods to identify segregations, inclusions in the seam and as semi-quantitative method to locate critical chemical elements such as oxygen for this type of welding. The appearance of any of these will impact the resulting mechanical properties of the joint.

3. Results and discussion

This section reports the effect of different parameter window investigation on the keyhole geometry as well as their influence on the weld seam quality. Those are: beam shapes included in Table 1, welding speed at given oscillation frequency and shape frequency at given process speed. To conclude, a detailed metallographic examination is presented.

Influence of beam shape

Welding trials were performed with the different beam shapes with a width range of parameters comprising laser power between 2,4-3,6kW, welding speed up to 18m/min and shape frequency up to 1 MHz. Initial comparative was performed attending to penetration depth, interface width and presence of defects at the interface, as voids(pores) or cracks (Fig.).

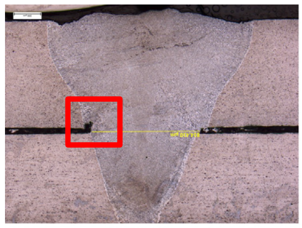


Fig. 3 Voids in the weld bead at the interface of two Al sheets

Beam shapes defined as infinity and spiral have provided better results than the other beam shapes tested in these trials according to the stablished quality indicators

Table 2 Comparative analysis of the different beam shapes

Beam Shape	Interface Width	Penetration	Interface defects
Two spots	−	−	− −
C+spot	+	−	− −
Spot+ring	−	+	− −
Pyramid	+	+	− −
Infinity	+	+	+
Spiral	+	+	+

Influence of welding speed

Fig. represents the measurements of seam width at upper surface, seam width at the interface of different welding trials performed with the spiral shape at oscillation frequency of 11kHz and 2,6 kW power. Penetration depth in the second plate is also presented.

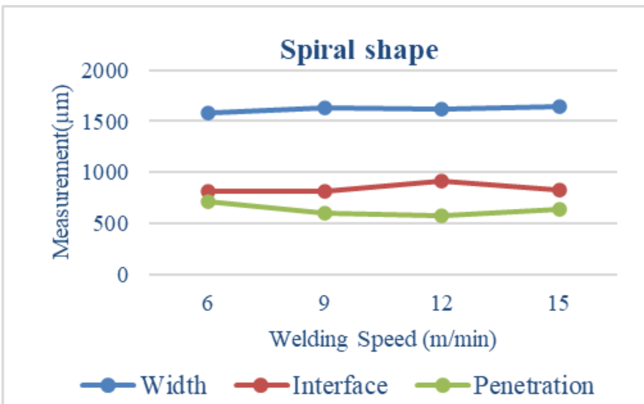


Fig. 4 Influence of welding speed on seam geometry for spiral dynamic shape

Attending to geometrical characteristics as seam width and weld penetration, slightly differences in weld width at the interface are achieved from 6m/min to 18m/min. In terms of penetration, slightly reduction (0,15mm) is observed increasing the welding speed from 6m/min up to 12m/min. The most significant effect is observed in the penetration depth range between 570 and 730µm keeping it within 20% variation in a wide range of feed rate speeds from 6 to 15m/min.

Analogous behavior as presented in Fig.4 for spiral dynamic shapes is observed in welds performed with the infinity shape (Fig.5). In this case the penetration depth is 0,2mm higher at 18mm/min that at 12m/min.

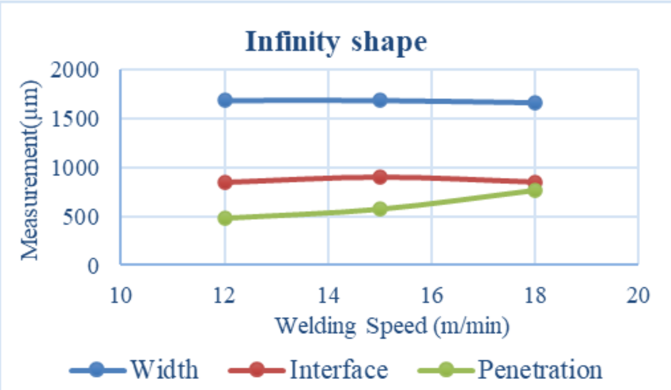


Fig. 5 Influence of welding speed on seam geometry for infinity dynamic shape

It must be considered that the frequency in CBC laser is related with the time to complete the path of the entire shape. Considering the infinity shape for illustration (Fig.2) the shape frequency is the inverse of the time to complete the shape pattern. The overlap length (D) between the shapes depends also on the welding speed and this parameter influences the resulting welding process (Fig. 2). Considering 11kHz as shape frequency and the width of infinity shape 0,26mm approximately, the shape overlap at 12m/min, 15m/min and 18m/min is 0,25mm, 0,24mm and 0,23mm respectively. This little parameter deviation, shape overlap distance in increments of 10µm, most likely cause the penetration varies so little at increased welding speed. Although this trend should be further examined, it will potential enable to achieve wider parameter window for process qualification. This will be advantageous in laser welding of complex geometries or curves with small radius where welding speed is usually reduced due to limitations of the positioning systems.

Influence of shape frequency

Different welding trials were performed for the spiral beam shape at 6m/min in order to determine the influence of the shape frequency on weld width (at top sheet surface and at the interface) and penetration depth. As it observed in Fig. the weld width at the surface is almost constant at different frequencies between 1kHz up to 1MHz. At the interface, the weld width reduces significantly at frequency higher than 111kHz. The penetration depth is higher at low frequencies (up to 11kHz). Higher welding speeds should be tested in order to check if same behavior is observed or by contrast the combined effect of shape overlapping/welding speed/shape frequency would lead to increased depth penetration.

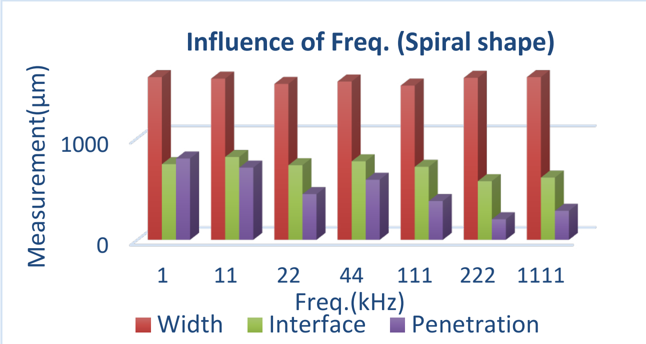


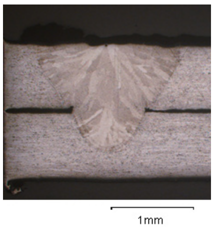
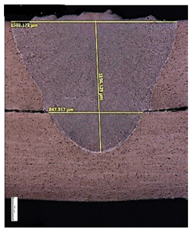
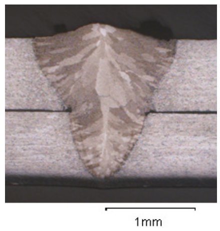
Fig. 6 Influence of shape frequency in weld bead width (surface, interface) and penetration depth

Metallographic analysis

Through the first analysis, it is assessed that spiral and infinity shapes with hollow geometries reduce the occurrence of weld defects in overlap configuration. Independently of process speed, power and frequency, infinity and spiral showed best results from all tested shapes. Quality criteria such as lack of defects, penetration depth and width at interface were considered. Examples of adequately welded parts at 15m/min and 18m/min (Infinity shape) and 6m/min (Spiral shape) are shown in

Table 3. In all cases columnar growth of the dendritic grains is observed.

Table 3 Macrographs of Al welded beads performed at different welding speeds and beam shapes

		
Infinity (15m/min)	Infinity (18m/min)	Spiral (6m/min)

SEM analysis performed in different regions of the weld bead show similar particles that those initially present in the base material, which are mainly Al12 (Fe, Mn)3 Si constituents:

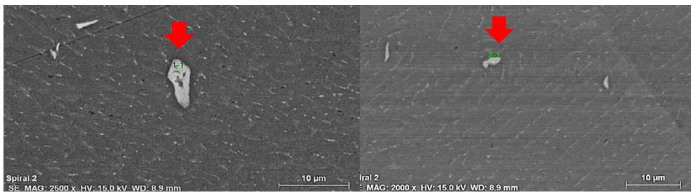


Fig. 7 SEM Image of different regions of the weld metal. Particles similar to those present in base material

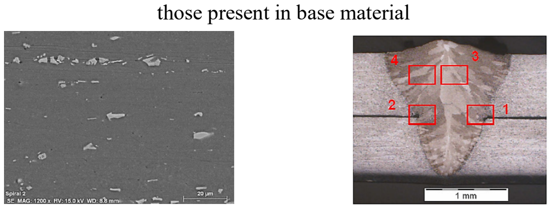


Fig. 8. SEM Image from the base material. Al12 (Fe, Mn)3Si constituents (left), Regions where EDX analysis was undertaken (right)

EDX analysis was performed in order to achieve a semiquantitative analysis of the composition (Oxygen, Silicon, Manganese and Iron) in four different regions of the weld bead.

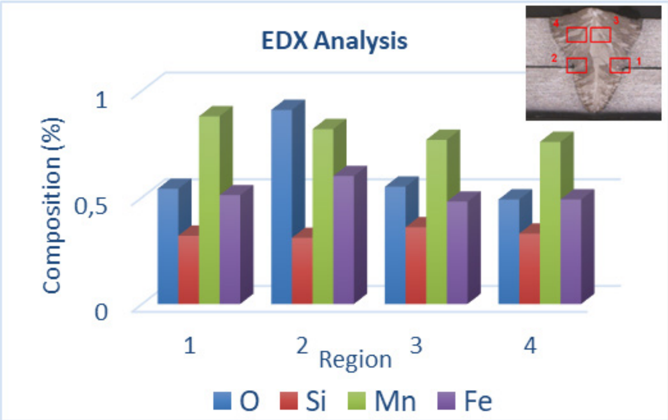


Fig. 9. EDX Analysis on different regions of weld bead. Oxygen, Silicon, Manganese and Iron content

Bar chart included in Fig. 9 shows no significative difference in the composition of the selected areas. However, in the region 2, at the interface between the two sheets a deep analysis by SEM show some inclusions which are mainly aluminum oxides (Fig. 10).

Inclusions of aluminum oxide inside the weld metal will have undesirable impact on mechanical properties of the weld joint. Optimization of welding parameters is required in order to reduce/avoid these inclusions in the weld metal.

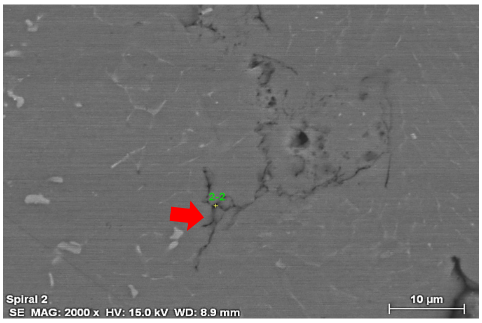


Fig. 10. SEM image of region 2: Inclusions of aluminium oxide inside the weld metal

4. Conclusions

We introduce a novel high-precision laser welding system at e-mobility market-enabling throughput rates. Its capability of accurately controlling beam shape at high frequency has been explored towards process qualification for challenging joining applications, such as overlap welding of aluminium alloys with partial penetration.

The main conclusions drawn from this work can be summarized as follows:

- Dynamic beam shapes created with spiral and infinity oscillation patterns have been explored for this welding application in terms of seam geometry: weld interface width and penetration depth. Initial metallographic analysis has been also undertaken.
- Increase the frequency of the shape over 10 kHz provides stable keyhole welding with required penetration depth and weld width at the interface
- Beam shapes tailored designed with shape frequency over 10kHz enables welding speed up to 18m/min in Al overlap joints with low defects occurrence, first time to the best of our knowledge.
- Laser beam shaping at high frequency enlarges the process window parameters in terms of welding speed to achieve weld beads with stable seam geometry width and penetration depth.

As next steps, the combined effect of shape frequency, welding speed and overlap distance will be studied to identify the influence of higher frequency on welded joints. Further work is required in order to overcome existing challenges as: reduction of aluminum oxide inclusions and minimization of defects and to ensure robustness and stability of this high throughput welding process.

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