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Spatter Reduction in Coherent Beam Combining Laser Welding of Aluminum through Intensity Distribution and Deflection Frequency Adjustment for Low Penetration Wide Welds in Transition Mode

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Abstract

Aluminum is an important material for lightweight construction and is particularly environmentally friendly due to its 100 percent recyclability. However, unstable melt pools and keyholes of this material make it more susceptible to spatter during laser beam welding. Proven methods to stabilize the melt pool and reduce spatter are focus adjustments, beam oscillation or tailored beam shapes. Using Coherent Beam Combining (CBC), Dynamic Beam Lasers (DBL) can push a wide variety of intensity distributions with different oscillation frequencies on top of the melt pool, that can stabilize the melt pool and control the keyhole dynamics. This can further help not only to achieve a spatter free weld, but also to aim for a very low penetration depth, suitable for special welding scenarios like laser powder bed fusion (LPBF) or foils in electromobility. This study investigates the general suitability of complex DBL systems with dynamic intensity distribution for spatter-free transition mode welding of aluminum flat seams in different frequency ranges. The evaluation of high-speed imaging and weld quality, including metallographic examination, is presented and discussed.

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Keywords: CBC; Welding; Aluminum; Spatter; Coherent Beam Combining; Intensity Distribution; DBL; Dynamic Beam Laser; high-speed imaging;

1. Introduction

Laser beam welding is becoming increasingly popular in industrial applications due to the improved availability of lasers with different wavelengths at high power levels. The unique features of lasers are their high precision, high welding depth without seam preparation, and small heat-affected zone. The result of every welding process is the weld seam, which is described by its phase composition and geometry. The geometry is particularly influenced by the welding speed, the wavelength of the laser, the focus position, and the intensity distribution, among other factors. The intensity distribution achieves this by influencing the melt pool behaviour and capillary dynamics. [1] Unlike conventional lasers with Gaussian or top-hat profiles and FRM (flexible ring mode) lasers, DBL (dynamic beam shaping) lasers offer much more complex and precise control over the intensity distribution in the melt pool via what is known as coherent beam combining (CBC). E.g. for Steel, such special beam shapes of a DBL can be used to specifically influence seam geometries, especially when the oscillation frequency is increased. [2] Such dynamic intensity distributions also have an influence on the phase composition. [3] DBL Lasers are also able to impact greatly keyhole geometry using different beam shapes and oscillation strategies. [4], [5] Aluminum however is an important material for lightweight construction and is particularly environmentally

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friendly due to its 100 percent recyclability. But its low density and high thermal conductivity make it more susceptible to spatter during laser beam welding, which is also due to unstable melt pools and difficult keyhole dynamics. In LPBF processes the low viscosity and low surface tension of aluminum can cause the molten pool to move more freely, which can lead to disturbed melt pool dynamics and damping capacity for oscillations, resulting in more spatters. [6] For aluminum alloys, crack-reduced welding has already been demonstrated with a DBL, but only for deep penetration welding. [7] Studies of laser beam welding on thin aluminum sheet metal show that circular oscillations can be used to specifically reduce spatter and even control its direction. [8] Furthermore such spatters can be supressed for aluminum welding using adjustable-ring-mode lasers: The leading edge of the melt pool is preheated by the ring, which helps in reducing sharp fluctuations of the absorption rate of the aluminum. This is important, because the high reflectivity and high thermal conductivity of aluminum initially absorbs laser energy less efficiently, so the process can swing quickly between insufficient melting and intense localized heating. [9] Chebil et al. show that during the laser powder bed fusion process on aluminum alloys, spatter characteristics such as speed, angle of ejection, and size increase with increasing intensity. [10] Additionally, low-boiling alloying elements, especially Mg and Zn, can evaporate under the laser radiation and lead to inconsistent recoil pressures that induce keyhole wobble and favour molten material bursts that lead to significant spatter events. [11] The state-of-the-art shows, that different beam shapes and oscillation strategies can successfully be used to tackle the spatter inducing characteristics that aluminum alloys bring into laser welding. This is especially true for deep penetration applications. In some scenarios, deep welding is not desirable; welding should primarily be carried out in a shallow area. Areas of application can range from 3D printing and surface treatments to delicate welding in the field of electromobility and battery cell production. The aim of this work is to apply the hypotheses and experiences gained from deep penetrations welding into transition mode welding and to investigate the suitability of complex DBL systems with dynamic intensity distribution for spatter-free transition mode welding of flat aluminum seams in different frequency ranges.

2. Experimental setup and Methodology

2.1. Experimental Setup

The welding tests carried out in this study were performed using the Dynamic Beam Laser DBL 16 kW (Civan), delivering laser radiation with the wavelength of 1064 nm. This laser system allows the intensity distribution (beam shapes) to be precisely adjusted electro-optically without moving components, enabling the welding process to be flexibly adapted to different materials and seam requirements. The core method of this technology is based on the Optical Phased Array (OPA), in which the beams of multiple single mode fibre lasers are individually combined in the far field. This allows the laser beam to be controlled in the x, y, and z spatial axes and its intensity distribution to be flexibly adjusted. [12] Typical beam shapes or figures that can be generated with the laser are dots, lines, circles, ellipses, but complex combinations with individual adjustments tailored to specific welding tasks are also possible. The laser beam can achieve frequencies of up to 40 MHz, which is however limited by the number of points that are used to build a certain beam shape.

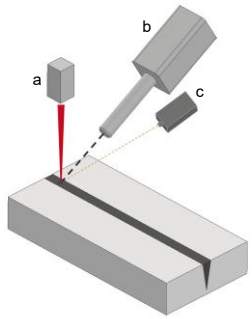


Fig. 1. Experimental setup with high-speed camera and illumination laser – (a) laser; (b) high-speed camera; (c) illumination laser.

The welding process was recorded with a monochrome high-speed camera SA4 (Photron) and an illumination laser Cavilux HF (Cavitar), as can be seen in Figure 1. The camera and illumination laser were directed directly at the keyhole centre to examine capillary dynamics and the formation of spatter and smoke. The camera was calibrated using a scale in accordance with DIN865/866. The recordings were made at a frame rate of 20,000 fps. Since the aim of the study is the reduction of spatter using different beam shapes and frequencies, bead-on-plate welds were performed. The base material used for this was the aluminum alloy EN AW-5754 (Table 1).

Table 1. Chemical composition wt. % Base material.

Material	Chemical composition wt.%						
	Mg	Si	Cu	Mn	Zn	Cr	Fe
EN AW-5754	2,63	0,263	0,0644	0,306	0,0494	0,0615	0,306

2.2. Experimental plan and applied process parameters

The tests focused on achieving comparable results using different welding parameters for four different intensity distribution patterns. The aim was to analyse capillary formation and dynamics, weld seam geometry, spatter formation, and smoke generation. Four different intensity distributions were generated, as shown in Figure 2: Dot (a), Long Line (b), Big Circle (c), and Dot Circle (d). The Dot is comparable to a conventional laser spot. Among other things, the type of joint remained unchanged for all welds, with only blind welds being performed to ensure reproducibility and the comparison of different welding parameters. In addition, the setup and distance of the laser to the base material remained unchanged; all welds were performed at a focus position (z-axis) of 391 mm and a table setup of 80 mm, which is the in-

focus-position for this laser. The projection angle of the figures was 90° for all welds. All welding tests were performed at a laser power of 9 kW and a welding speed of 18 m/min. For the four beam shapes generated, the frequencies were varied at 10 or 100 kHz, and the gas flow was also varied at 5 l/min Shielding gas (argon). (Table 2)

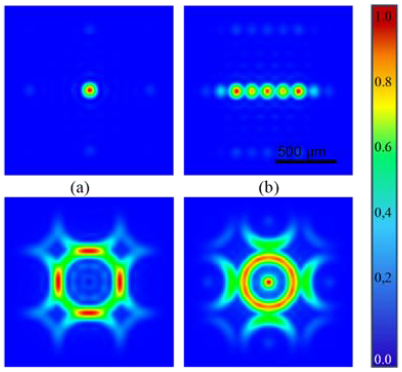


Fig. 2. Dynamic beam shapes - (a) Dot; (b) Long Line; (c) Big Circle; (d) Dot Circle.

As determined in previous studies, changing oscillation frequencies for a single dot does not affect the welding result with the used laser system. Thus, the frequency of 100 kHz was not examined for the Dot shape, which is intended to simulate welding with a conventional laser.

To ensure that the process was in the transition zone between heat conduction and deep welding, attention was paid to the presence of steam clouds (partial evaporation) surrounding the process.

Table 2. Welding parameters.

Beam Shape [-]	Frequency [kHz]	Power [kW]	Welding Speed [m/min]	Argon [l/min]
Dot	10	9	18	0/5
Long Line	10/100	9	18	0/5
Big Circle	10/100	9	18	0/5
Dot Circle	10/100	9	18	0/5

2.3. Evaluation methods

Macro sections of the weld seams were made to evaluate the weld geometries. The weld seam depth and surface area were measured using the ImageJ tool.

In earlier work spatter detection has been performed by different methods, such as via the use of Kalman Filters [13], Shape and Angle similarity functions for the particles [14], [15] or ,similar to the method of this paper, linking particles together based on their motion away from the weld pool. The individual pictures of the high-speed camera were edited to equalize the exposure and to increase the separation between the single particles and the background. The spatter analysis was then performed with a custom python script. The script consisted of four separate parts:

1. Image Preprocessing
2. Search for Points of Interest
3. Linking of Points of Interest
4. Filtering of erroneous particles

In the first step areas in the pictures are designated as zones where no particles are tracked, this includes the top and bottom areas that include information about the recording equipment, as well as the weld pool. In the second step points of interest are defined by their size and total brightness. In the next step these points are linked by a specialized version of the Crocker-Grier Algorithm [16] with added bias towards radial motion away from the centre of the weld pool. In the last step particle tracks are filtered, based on a minimum movement distance between the frames, whether their direction of travel is along the axis of background motion and whether they are only along the edges of the earlier defined no-track zones. For the final evaluation, the last 520 frames before the beginning of the Laser ramp down are considered. This pipeline is shown for a small number of frames in Figure 3.

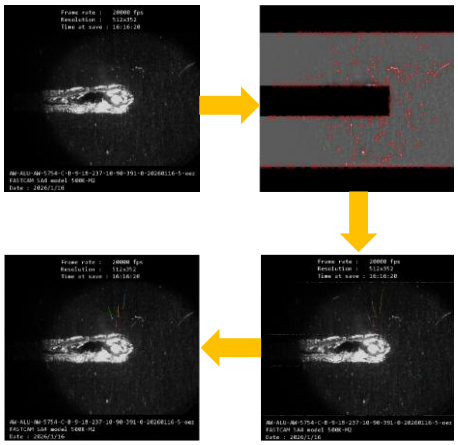


Fig. 3. Image Processing Pipeline. (Long Line, 10 kHz, 18 m/min, 9 kW).

3. Results and Discussion

3.1. Effect of beam shape and frequency on spatter

The different beam densities led to differing amounts of spatter. The Dot and Line shapes were the only ones where significant spatter was observed, as shown in the diagram in figure 4. For the Dot shape there were around 1600 spatters observed in the 520-frame measurement window. For the Line shape nearly 2000 particles were observed, which is approx. 22% more than for the dot shape. Both the Dot and the Line Beam Shape are characterized by significant spatter events. In these events many liquid metal spatters are ejected from the weld pool, which may be due to the sudden vaporization of alloying elements such as Mg and Zn. The Dot and Long Line Shapes tend to have higher local intensities compared to Dot

Circle and Big Circle, which can favor the early evaporation of the alloying elements leading to more spatter events and generally more spatter.

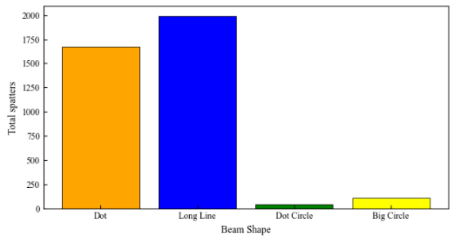


Fig. 4. Total spatters Diagram for 10 kHz and different Beam Shapes.

For both the Dot Circle and the Big Circle nearly no spatters could be measured by the program. On the one hand, spatters, when they occurred, were particularly small and therefore fell below the program's threshold. Small spatters are also less problematic than larger spatters, as they are less likely to roll into “snowballs” on powdered surfaces or bake onto them. They are also easier to remove from the laser line of sight with a conventional cross jet. Therefore, they do not pose a great risk of damage or downtime to the system due to maintenance or reworking of the workpiece. Overall, a significantly smoother melt bath surface was observed in the high-speed images in the Big Circle, which may have led to the reduction in spatters. However, the Dot Circle did have a spatter ‘event’, where the keyhole collapsed and spattering could be observed. The overall, more even intensity distribution helps to reduce temperature peaks in and around the weld pool which seems to be the cause of the significantly reduced spatters. Due to uneven lighting and reflection from the aluminum, making quantitative assertions about the spatter was difficult. We hope that using new lighting concepts and the utilization of a high-speed camera with higher resolution, more accurate outcomes can be achieved.

3.2. Effect of beam shape and frequency on weld seam geometry

The geometry of the weld seams can be influenced by both the intensity distribution and the frequency. To be able to carry out a comparable investigation, all welds were performed with the same welding power of 9 kW and a welding speed of 18 m/min. Since the protective gas used in the tests did not produce any noticeably better or worse results, only the tests without protective gas are examined here in terms of their geometry.

The macro sections in Figure 5 show the different penetration depths of the weld seams achieved with only varying oscillation frequency and different intensity distributions. Beam shapes such as Dot and Long Line, which have a locally focused intensity on one or more points, tend to result in a deeper and wider weld seam, which is usually the goal of traditional welding. Figures that have a wider intensity distribution over the area, such as Big Circle and Dot Circle, tend to produce a very flat seam, which is suitable for processes that operate in the transition area between heat conduction and deep welding, but are not intended to create a deep seam.

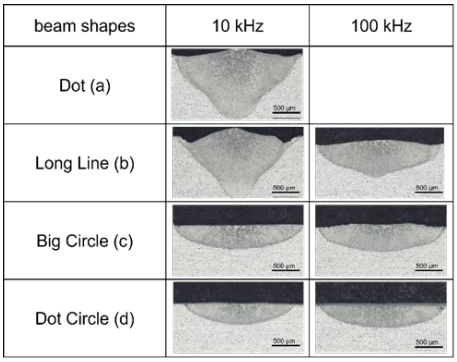


Fig. 5. Weld seam cross-section.

The differences in seam geometry become even more apparent with increasing oscillation frequency. This influence seems to be particularly significant in the case of narrow, non-circular figures (e.g., long line), since the weld seam depth has almost halved, as shown in Table 3. There is also a clear difference in the seam height. For the circular beam shapes there appears to be a positive correlation between higher oscillation frequency and the surface area of the weld seam, although it is very small compared to the long line difference.

Table 3. Geometrical Analysis of the Weld seams.

Beam Shape	Frequency [kHz]	Area [mm^2]	Depth [mm]
Dot	10	1,7986	1,212
Long Line	10	1,6446	1,264
	100	1,1700	0,681
Big Circle	10	0,7206	0,418
	100	0,8627	0,410
Dot Circle	10	0,6718	0,404
	100	0,7042	0,406

The welds of Big Circle and Dot Circle, which have a wider intensity distribution over the surface, have almost identical weld seam depths when compared to each other. The seam depths here are approximately 0.406 to 0.418 mm. It is interesting to note that the welds of Dot Circle show cracks in the weld seam at both 10kHz and 100 kHz frequencies. The crack depths are approximately 0.343 mm at 10 kHz and 0.312 mm at 100kHz, measured from the weld seam surface. With Big Circle, a crack can also be seen in the middle of the weld when welding at 10 kHz. However, this crack formation is no longer visible at higher frequencies, in this case 100 kHz. This can also show a crack reducing tendency of higher oscillation frequencies with aluminum using wide circular intensity distributions. The higher oscillation frequency of the DBL helps to further reduce local intensity and temperature peaks which result in spatter free wide welds with narrow penetration. This is especially helpful as a preliminary investigation into the potential application of dynamic laser

beam shaping in laser powder bed fusion (LPBF). For this purpose, the objective is to produce flat, wide weld pools with minimal weld bead height under spatter-free conditions. This is particularly important because spatter formation can lead to defects in LPBF processes due to snowball effects, in which accumulated particles compromise subsequent layers. The results, as shown in Figures 4 and 5, demonstrate the feasibility of this approach and highlight its potential for improving process stability and part quality in the LPBF process, which can be part of further investigations.

4. Conclusion and Outlook

The investigations showed that a DBL laser could be used to produce flat seams without spatters in the transition area on aluminum. It was demonstrated that higher frequencies and larger intensity distribution diameters produce flatter seams without spatter, even on aluminum. In some cases, increasing the frequency also reduced cracks in the centre of the seam. As already discussed in other studies, the significant influence of intensity distribution and frequencies on the seam geometry and microstructure is also evident here.

These experiments form the basis for further investigations in which the framework conditions of the welding process are further approximated to an application-oriented scenario in terms of welding speed, maximum seam depth, seam geometry width, and highly spattering aluminum alloys, for example in the field of 3D printing.

In the future the results from this research can be used to further improve the tracking of weld spatter. Either by using the new hardware, through improvements to the current tracking algorithm or using the tracked particles as a database for the training of a CNN (Convolutional Neural Network). The program, which will then be expanded to include AI functions, should enable a precise analysis of different materials and welding processes regarding spatter and weld seam geometry, and make it possible to compare different processes, particularly in terms of spatter and ejection behavior.

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