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Spatter occurrence when using laser beam oscillated welding for aluminum

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Abstract

In the past years, laser beam welding has evolved to a cutting-edge technology for high production facilities such as body-in-white manufacturing. Hereby, laser beam processing is characterized by a slender weld seam geometry and a comparably low heat input. However, the possible occurrence of spatters leads to quality issues, for instance the contamination of the part. Furthermore, a weakening of the weld joint induced by mass losses due to spatters can result in a production breakdown.

Following recent trends of laser beam oscillation techniques, this research has drawn attention to the quantification of the spatter formation and their trajectories depending on the oscillation pattern when welding thin-sheeted aluminum. Experiments were performed with a high-power diode laser with beam converter. Multiple oscillation patterns were realized by using a scanning unit, which allowed beam oscillations longitudinal and perpendicular to the feed direction. By doing so, the rectilinear welding velocity is superimposed by the oscillation of the laser beam with a significantly increased beam velocity, which lead to a reduction of the spatter formation in the weld pool. Moreover, the direction of the occurring spatters is mainly depending on the oscillation pattern. For instance, a more defined release of the spatters is accomplished by the means of a sinusoidal laser beam oscillation. Finally, the results show a reduction of the spatter occurrence with the application of a circular laser beam oscillation.

Keywords: laser beam welding; beam oscillation; spatter; aluminum

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1. Introduction

Modern automotive designs aim for a significant weight reduction for the car bodies. Therefore, thin-sheeted aluminum with high performance is a suitable material for automotive applications. However, the joining with laser radiation of aluminum alloys is challenging in terms of spatter formation. In the first place, spattering leads to a significant mass loss and thus a reduction of weld seam volume. Subsequently, spatters contaminate the part as well as the fixture and even more they can result in a damage of the laser optics, which in turn causes downtime or a production stop.

By now, several studies have shown attempts to prevent spatter formation due to multi focal welding[1,2], welding with laser beams from multi core fibers[3] and beam oscillation techniques[4,5,6]. With the development of remote laser beam welding of aluminum[7] and the challenges of joining dissimilar materials with laser radiation[8], several scanner optics with seam tracking and a narrow field for laser oscillation patterns were established in the market[9,10]. Consequently, these scanners enabled new opportunities on the basis of high frequent laser beam oscillation[11,12] for modern production facilities. Accordingly, this paper assesses the quantification of the spatter occurrence depending on the velocity of the laser beam and the oscillation pattern when welding aluminum.

In the first section, the experimental set-up is described. The second section gives an overview of the methodology to quantify the spatter. Finally, the results are discussed regarding the spatter occurrence.

2. Experimental Set-Up

For the experiments a diode laser with beam converter was used with an output power of 4.4 kW and a beam parameter product of 4 mm x mrad. By doing so, the system allowed a use of a minimal fiber core diameter of 100 µm. In fact, the focal diameter resulted in 290 µm due to the magnification of scanner optics of 2.9. At the same time, this scanning device allowed a laser beam oscillation within feed direction and perpendicular to the feed direction. Concurrently, lissajous-figures were realized by a superposition of both oscillation directions. In this case, the rectilinear feed rate is also superimposed with the laser beam oscillation. Accordingly, the velocity of the laser beam on the work piece surface is accelerated significantly. To obtain the trajectories of the spatters, no cross jet or shielding gas was used.

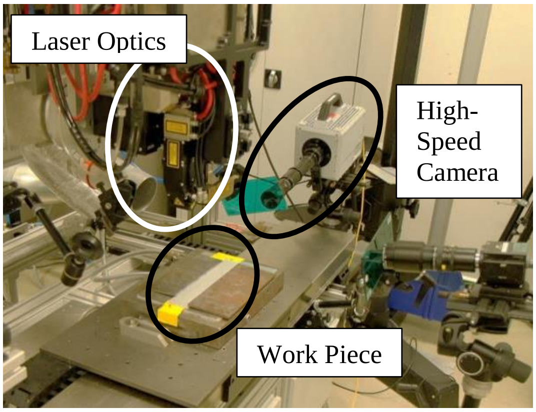

Fig. 1. Experimental set-up to quantify the spatter occurrence when welding aluminum.

The presented investigations were performed with cleaned aluminum parts to avoid spatter formation due to a random contamination of the work piece. In order to display common conditions, the aluminum alloy AlMgSi1 was used for the experiments which is a common material in body-in-white manufacturing. 200 mm long bead on plate welds were performed.

In order to quantify the spatter occurrence, a high-speed camera was used to observe the process within the feed direction in a wide angle, as shown in Fig. 1. For this investigation, a frame rate of 250 Hz is sufficient to quantify the spatter behavior when welding aluminum. However, a notch filter is necessary to eliminate any reflections in the range of the laser wave length at 1090 nm.

3. Methodology

The temperature of releasing spatters exceeds the melting temperature of the material. Therefore, the surface of the spatters emits thermal radiation, which can be detected by the high-speed camera system without any additional illumination. In order to obtain detailed information about the spatter occurrence, the resulting videos were analyzed with the image processing application "ImageJ"[13]. Thus, Fig. 2 illustrates a sequence of the welding process with sinusoidal beam oscillation with the laser power of $P_L = 2.5$ kW, a lateral scanning frequency $f_y = 100$ Hz, a lateral scan amplitude of $w_y = 1.5$ mm and a feed rate of $v_B = 6$ m/min.

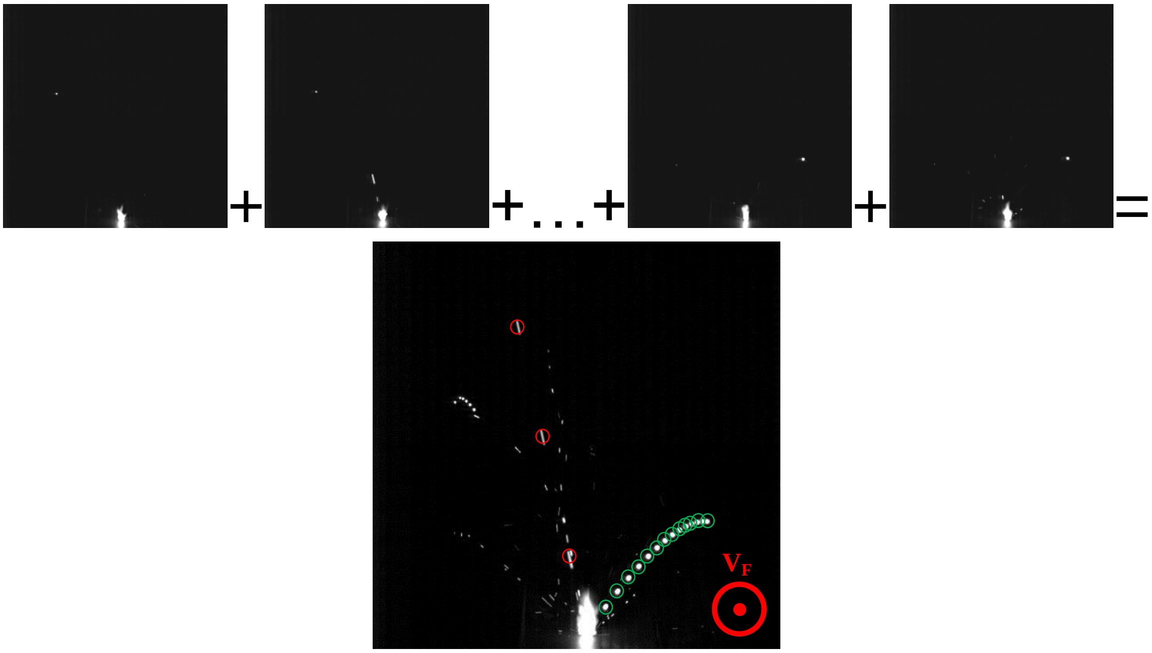

Fig. 2. Superposition of 17 single frames to a summarized picture of the welding process to display the spatter occurrence when welding with sinusoidal beam oscillation; $P_L = 2.5$ kW, $f_y = 100$ Hz, $w_y = 1.5$ mm, $v_B = 6$ m/min.

As shown in Fig. 2, every single frame of the video was aggregated to a summarized picture. For the evaluation, coherent areas of white pixels are interpreted as spatters. Therefore, the total ratio of black areas to white areas in the summarized picture is an indication of the entire spatter formation induced by the welding process. However, comparably small spatters, as highlighted by red circles in Fig. 2, with i.e. a diameter of 0.4 mm and lower had relatively high speeds of greater than 5.9 m/s. On the contrary, with an increasing spatter diameter the velocity of spatters decreased. For instance, the green marked spatter in Fig. 2 with a diameter of 1.05 mm had a speed of 1 m/s. In conclusion, slow spatters were displayed more often in the summarized picture due to the constant frame rate. As a result, big spatters have a higher impact on the evaluation because of their size as well as their speed due to multiple illustrations.

In addition, the summarized picture not only leads to the quantification of the spatters, but also to the trajectories of every single spatter. As a result of stringing together multiple images, a detailed version of the trajectory is visualized exemplarily by red and green circles in Fig. 2.

Following Fig. 3, the metal vapor coming out of the capillary was detected by the means of an algorithm. Therefore, the influence of the metal vapor on the evaluation has to be minimized. The algorithm removes connected white areas of pixels by using suitable filtering methods like the roundness of connected pixels and the size of connected pixels to separate the spatters from the metal vapor.

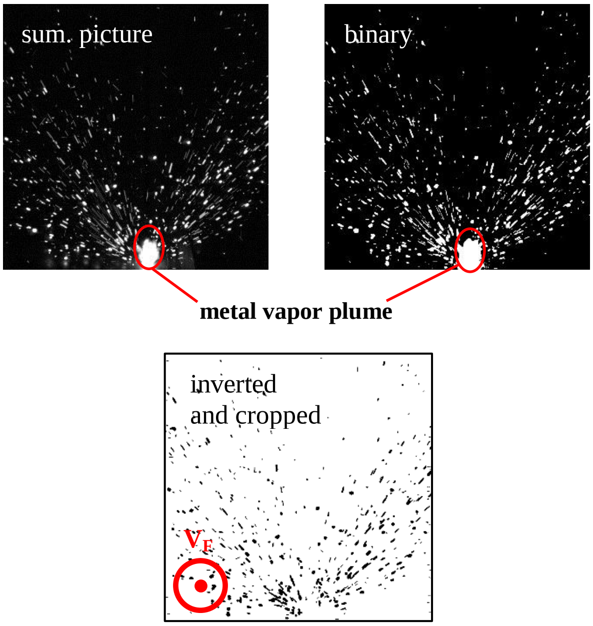

Fig. 3. Superposition of multiple frames to a summarized picture of the welding process by the means of sinusoidal laser beam oscillation to display the spatter occurrence; P_L = 2.5 kW, f_y = 100 Hz, w_S = 1.5 mm, v_F = 4 m/min, l = 200 mm.

4. Results and Discussion

Initially, the influence of the feed rate for welding the aluminum alloy AlMgSi1 on spatter formation is investigated. First, the welding process was limited to rectilinear welding to keep the interfering factors small. As a result of varying the feed rate, spatter formation with randomly distributed moving directions could be observed (Fig. 4). Furthermore, the average spatter size was decreasing with increasing feed rates. Analyzing the resulting summarized images, few spatters have an elongated shape. This can be explained due to the comparably large exposure time of the camera (0.5 ms) in combination with a very high speed (≈ 5.9 m/s) of the observed spatters.

In the first image of Fig. 4, the resulting image at a welding speed of 2 m/min shows a black to white ratio of the resulting image of 50 %. The spatter occurrence of laser beam welding with a feed rate of 4 m/min generated about 40 % less spatters than with the slow feed rate (see Fig. 4). Likewise, the feed rate was further increased to 6 m/min in order to obtain less spatters. Accordingly, the least spatter formation resulted from the highest investigated feed rate of 6 m/min and is 88 % less than the generated spatters of welding with 2 m/min. By increasing the feed rate, the process improved in terms of a more robust welding regime for aluminum. Subsequently, following investigations were conducted with a feed rate of 6 m/min.

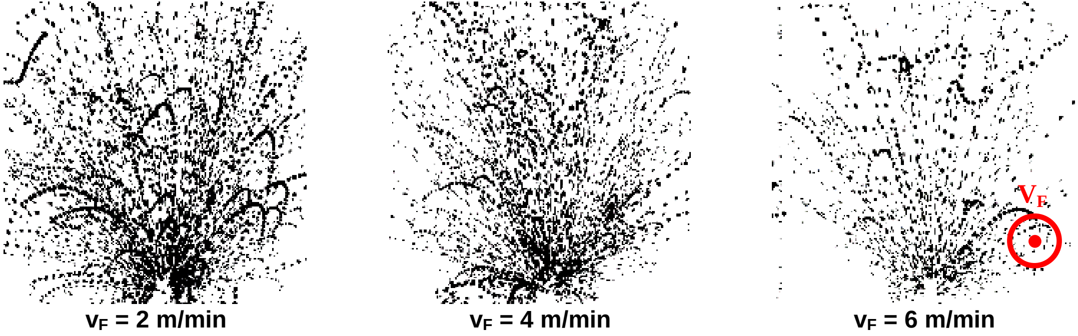

Fig. 4. Reducing spatter occurrence for rectilinear welding with P_L = 2.5 kW, d_f = 290 µm, l = 200 mm.

Conversely to an increasing feed rate, another approach to reduce spatter formation is to oscillate the laser beam on the work piece surface. Using superimposed sinusoidal beam oscillation perpendicular to the rectilinear feed direction the local velocity of the laser beam is increased depending on the feed rate, the oscillation frequency, scan width and the oscillation pattern. For the experiments the feed rate of the oscillating laser beam resulted in 55 m/min. In relation to rectilinear welding, the spatter formation could be decreased about 97 % by the means of beam oscillation. However, an increase of these parameters results in a decrease of the welding depth.[11] It could be found that an acceptable relation of welding depth to spatter formation is achieved by a combination of a scanning frequency of 100 Hz with a scan width of 1.5 mm.

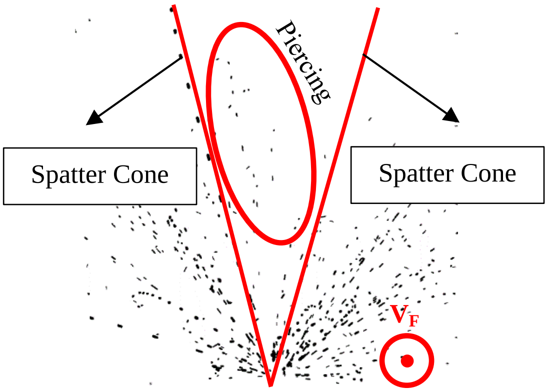

Fig. 5. Spatters resulting from welding by the means of beam oscillation with P_L = 2.5 kW, d_f = 290 µm, f_y = 100 Hz, w_y = 1.5 mm, v_F = 6 m/min, l = 200 mm.

Fig. 5 shows the spatter formation for sinusoidal laser beam oscillation at a laser power P = 2.5 kW, an oscillation frequency of f = 100 Hz, a lateral scan width w_y = 1.5 mm and a feed rate of 6 m/min. The direction of the spatter formation is predominantly in two cones on the sides of the process (see Fig. 5). A few spatters scattered in direction to the laser optics, which basically came from the piercing process when the vapor capillary was formed at the very beginning of the weld seam. However, the total amount of generated spatters, displayed in Fig. 5, results in a reduction of about 50 % of the spatter volume compared to rectilinear laser beam welding with a feed rate of 6 m/min.

Fig. 6. Spatters resulting from welding by the means of beam oscillation with P_L = 2.5 kW, d_f = 290 µm, $f_{x,y}$ = 100 Hz, $w_{x,y}$ = 1.5 mm, v_F = 6 m/min, l = 200 mm.

Moreover, by using circular beam oscillation as seen in Fig. 6, the amount of generated spatters can be reduced to about 11 % compared to rectilinear welding at 6 m/min. Although the spatters are comparably small, they have very low speed and scattered in random directions. Overall, the average spatter diameter was very low (d_S = 0.6 mm) so that the optics and the work piece were not to be hit by a high volume of spatters resulting from a circular oscillating laser beam pattern.

5. Conclusion and Outlook

In this paper, it could be shown that spatter occurrence can be significantly reduced compared to rectilinear welding aluminum alloys by using laser beam oscillation. The circular oscillation pattern reduced the spatter occurrence in general compared to rectilinear welding. However, an increase of the beam velocity lead to a reduction of the spatter occurrence independent of the process design. Furthermore, the directory of the spatters could be influenced by the means of the oscillation pattern. Almost no spatter formation was observed in the direction of the laser optics with the application of laser beam oscillation. The sinusoidal oscillation pattern explicitly lead to two spatter cones on the sides and less spatters towards the laser optics.

In addition to this study, future research should address explicitly the spatter formation mechanisms in order to prevent spatters when welding aluminum by the means of laser radiation.

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