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Inline repair of blowouts during laser welding

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Abstract

In a current laser welding production process of components of stainless steel, a butt joint configuration may lead to failures in the form of blowouts, causing an unacceptable welding quality. A study to improve the laser welding process was performed with the aim of solving the problem by designing a suitable pattern of multiple small laser spots rather than a single spot in the process zone.
The blowouts in the process are provoked by introducing small amounts of zinc powder in the butt joint. When the laser heats up the zinc, this rapidly evaporates and expands, leaving the melt pool to be blown away locally. Multiple spot pattern designs are tested. Spot patterns are produced by applying diffractive optics to a beam from a single mode fiber laser.
Results from welding while applying spot patterns both with and without trailing spots are presented. Data showing the power ratio between a trailing spot and two main spots as a function of spot distance is also presented.
The results of the study show that applying multiple spots in the welding process may improve the process stability when welding materials with small impurities in the form of zinc particles.

Peer-review under responsibility of the scientific committee of the Nordic Laser Materials Processing Conference 2017

Keywords: Beam shaping; laser welding; diffractive optical element (DOE); weld geometry, inline repair welding, laser spot pattern;

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1 Introduction

Lasers have been applied to areas in hybrid processes in which the ability to dose energy precisely temporally and spatially has found several applications in many other process areas, including grinding and milling Dubey et al. (2008). Especially hybrid solutions with lasers and traditional fusion welding processes such as Gas Metal Arc Welding (GMAW) have shown significant benefits Olsen (2009). This work focuses on the use of several laser spots generated from a single beam.

In a current laser beam welding (LBW) production process of components in stainless steel in a butt joint configuration, impurities in the form of zinc particles in the joint and other residues may lead to blowouts. These will destroy the final weld and may create parts which are not pressure-tight and may contain highly irregular surfaces.

This is almost similar to the well-known problem of performing overlap welding of zinc coated steel sheets, which results in the evaporation and expansion of zinc in the melt pool, leading to small "explosions" which cause the entire weld pool to be blown away. This generally leads to a weld of poor quality with large surface irregularities Graudenz et al. (2013), Bagger et al. (1992). The explosions are caused by the relatively low boiling temperature of zinc at 907 °C compared to the melting temperature of stainless steel (EN 1.430) at 1450 °C. Due to the rapid increase in temperature during LBW, the zinc is trapped and evaporates in the melt pool, causing local expulsions of the melt pool.

Residues of organic compounds like oil rapidly decompose and evaporate when making contact with liquid metal, as is the case in LBW; this may lead to problems similar to those caused when zinc evaporates Katayama (2013).

This work was carried out as an industrial case in which an edge butt joint between two round discs with a thickness of 2.2 mm was examined. A thin foil of 75 µm, with the same diameter as the discs, was placed between the two discs. The experiment entailed an attempt to weld together the foil and both of the discs. The principle can be seen in figure 1a.

Instead of trying to carry out a repair welding with a spot trailing behind the first spot, a different strategy was applied in this work, in which the high quality of a single mode beam combined with diffractive optics enables the forming of the beam into spot patterns. In this work, spot patterns with multiple trailing spots were examined; two trailing spots were offset slightly towards each side so that they would melt new material after the melt pool had been blown away. The principle is shown in figure 1b.

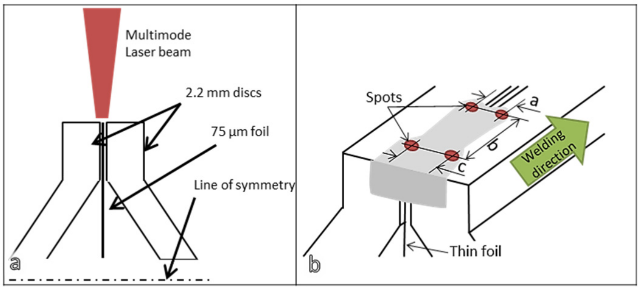

Figure 1 a) Welding principle in current production. b) One of the spot patterns applied to replace the multimode laser beam. Fig 1b from Hansen et al. (2015a)

2 State of the art

LBW with multiple spots has been known for many years and has found some specific niches.

Examples of previous work in which a laser beam has been combined with other laser sources or the laser beam has been reshaped:

- Xie et.al: have shown that using an extra laser spot to reduce the uneven cooling in a weld placed close to the edge of a sheet may prevent the forming of a centerline solidification crack, which would otherwise occur when the extra spot is left out Ploshikhin et al. (2004).

- Bagger et.al: have tested the reduction of hot cracking in welding aluminium by splitting the laser beam into a main spot and using two trailing side spots to reduce the cooling rate. They concluded that the penetration drops and that no improvements in quality can be observed. This work was performed using a multimode lamp pumped Nd:YAG laser with limited power and a relatively poor performing diffractive optical element Bagger et al. (2004). The lack of power and the relatively high beam parameter product from the lamp pumped Nd:YAG lasers most likely explain the lack of success.
- Trautman et.al: used two 3 kW lasers inline to increase welding depth in aluminium. They reached deeper penetration and generally performed sounder welds with less porosities Trautmann et al. (2004).
- Seefeld et.al: used a double spot optics on a laser beam from a CO_2 laser to carry out inline cleaning of the weld seam. The purpose of the first spot was to remove dirt and oxides before the second spot performed the actual weld Seefeld et al. (2004).
- Various versions of superimposing multiple LBW processes have also been performed, e.g. Kronthaler et al. used a Nd:YAG laser to make a keyhole welding and an extra diode laser to perform a surface conduction welding in the same weld pool. They conclude that the total process is more than a superposition of the two processes during which a better weld quality is achieved in the entire weld seam Kronthaler et al. (2011).
- Twin spot welding using multiple laser sources has been shown to have a positive effect on porosities Miyashita et al. (2013).
- Victor et.al: used a diamond turned element to produce two trailing spots which smoothen the surface at the edge of the weld. The angle of the weld toe was reduced from 125 degrees to 163 degrees Victor et al. (2011).

Laser has also turned out the be usable in other hybrid welding processing solutions, ranging from hybrid welding with a GMAW process Olsen (2009) to laser roll bonding of dissimilar materials Azaki et al. (2009).

Apart from the above-mentioned examples, so far beam shaping has only been used to a limited extent within LBW of metals. The authors believe the main reason for this is that either several costly laser resonators are required, or the quality of the beams has so far been insufficient.

When a weld pool is blown away, this causes the local weld geometry to become significantly different from its original design and consequently of a poorer quality. Therefore, it might be advisable to perform a repair weld. Instead of only performing this repair weld, when weld failure occurs, it is advisable to introduce a spot pattern with trailing spots. These spots melt material into a new weld pool, thus performing an inline repair process of the weld during which no weld failures occur. The trailing spots will also serve to even out irregularities where the melt pool was ejected. As of till now it has not been examined how much energy there should be in trailing spots in order to achieve same penetration as the main spots. None of the previous work has been performed with multiple small spots in the same melt pool. To examine this further, two sets of experiments were setup:

1. Bead on plate experiments with a trailing spot; in such experiments it is examined how power, distance and power ratio determine how deeply a keyhole from a trailing spot penetrates into an existing pool of liquid material.
2. An experiment on parts similar to those in production with different beam patterns, to examine how inline repair welding can be performed when blowouts of the melt pool occur.

3 Setup

The experiments presented in this paper were all performed using a 1 kW SM laser from IPG (YLR-1000-WC-Y11 2011 series) emitting a wavelength of 1075 nm.

The spot patterns were produced by changing the wave front of the collimated beam using a flexible beam shaping unit; this allowed for changes between spot patterns. The transformation phases of the individual spot patterns were calculated using a commercial iterative Inverse Fourier Transformation Algorithm (IFTA).

The resulting spot patterns were analysed and compared to the designed spot pattern. This was performed using an intensity sensitive CCD camera with appropriate attenuation. This was to ensure that the designed geometry and energy distribution was maintained in the spot patterns. Hansen et al. (2013).

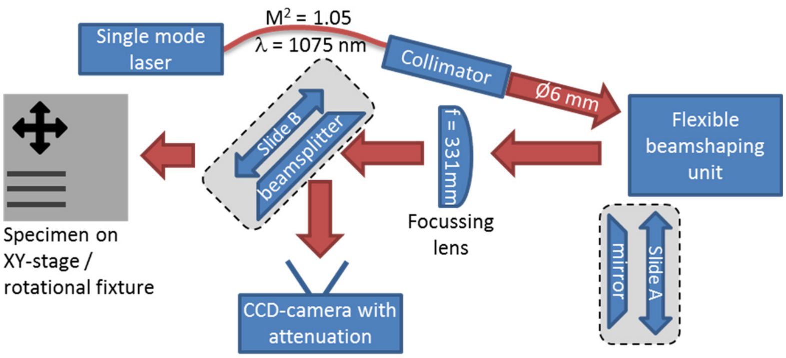

Figure 2 Outline of the setup principle. Slide A inserts a flat mirror instead of the flexible beam shaping unit, allowing use of an unmodified beam. Slide B inserts a beam splitter in the beam path, for a percentage of the beam to be directed to the camera for analysis.

For the design of spot patterns, only limited knowledge existed in terms of how spots in a line affect each other in terms of the depth of fusion and other weld geometry parameters Hansen et al. (2015b), Hansen et al. (2014). The literature search has shown that the amount of work performed with multispot patterns is limited. Therefore, limited knowledge exists on how the individual spots in the same weld zone interact in terms of fluid flow. Our literature study showed that existing work and research on welding with multiple spots mainly employed much larger spots, much higher energies and less intense spots, and therefore hardly any knowledge exists on using multiple small high intensity spots in the same interaction zone.

4 Experiments and results

4.1 Bead on plate experiments with trailing spots

The purpose was to determine the amount of energy needed in the trailing spots to produce a keyhole at a depth similar to that of the keyholes in the main spots. A series of experiments using three spots with varying power in the two main spots and the trailing spot were performed as bead on plate (BOP) welds.

The purpose was to determine how much power is required in the trailing spot to form a new keyhole in the melt pool, and how much energy is needed to form a new keyhole when the melt pool has solidified. These experiments were performed using varying distances between the two main spots and the trailing spot ("trailing spot distance" marked "b" in figure 3) and varying power ratios (power ratio = P2/P1) between the two main spots and the trailing spot. P1 denotes the energy applied in each of the main spots.

The purpose was to determine how much energy a secondary laser spot would need in order to form a keyhole with a depth similar to that of the melt pool in which the material was already molten.

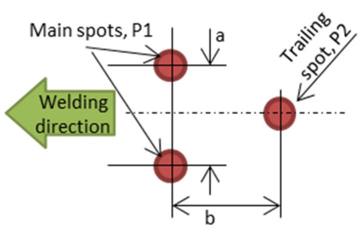

Figure 3 Spot pattern and definitions for bead on plate experiments

4.2 Experimental setup

All experiments were performed on 2 mm stainless steel, EN 1.4301, as bead on plate (BOP) with nitrogen as shielding gas. All spots in spot patterns had a diameter of 87 µm, and the travel speed was kept constant at 50 mm/s for all experiments. The chemical composition is given in table 1.

Table 1 Chemical composition for EN 1.430 (AISI 304) wt-%

	C	Si	Mn	P(max)	S	N	Cr	Mo	Ni	Fe
EN 1.4301	≤0.07	≤1.00	≤2.00	0.045	≤0.015	≤0.11	17.50-19.50		8.00-10.50	Balance
EN 1.4310	0.05-0.15	≤2.00	≤2.00	0.045	≤0.015	≤0.11	16.00-19.00	≤0.08	6.00-9.50	Balance

The distance "a" was set to 200 µm for all experiments. Previous work has indicated that if spots of this size are placed closer (distance "a") to each other than 250 µm, they will affect each other, and this will result in an increased depth of fusion and full fusion between each keyhole Hansen et al. (2015b).

To determine the depth of the keyhole formed by the trailing spot as a function of distance, b, a series of experiments were performed. The power ratio interval was set to 60-100%, and the power setting for the main spot was examined at 4 different values.

The distance between the main spots and the trailing spot was altered in order to examine how much the cooling would affect the keyhole formed by the trailing spot. Parameters are given in table 2.

Table 2 Parameters for the trailing spot experiments

		Interval	Changed with step size
Power, P1	W	170-310	45
Power ratio = P2/P1	%	60-100	10
Trailing spot distance, b	µm	100-200-400-800-1200-"fully cooled"	

The "fully cooled" distance between the main and trailing spots should be considered as a weld performed with a spot pattern without a trailing spot. The weld is later welded again using only a single spot.

4.3 Results and interpretation of cross sections

The experiments with a trailing spot revealed that the maximum depth of fusion is affected not only by the power in the main spots but also by the power ratio when the distance between the main spots and the trailing spot, b, is 800 µm or below. The effect was not seen in experiments with b = 1200 µm or for "fully cooled" distance. The effect was most evident at lower distances of b. For b = 100 µm, the depth of fusion as a function of power in one spot for 4 different power ratios is plotted in figure 5. Differences in microstructure and cooling profiles are not examined further in this work.

The cross-sections indicate the necessity of 60-70% power in the trailing spot for the trailing spot to penetrate the weld pool with b = 200 µm. The value is merely an estimation, as the solidification front from the trailing spots is not clearly distinguishable.

Figure 4 shows two cross-sections where only the power ratio P2/P1 has been changed. The depth of fusion for these is higher at the increased power ratio. It is therefore assumed that for all the applied values of P1 and power ratios, the trailing spot will re-melt the entire weld pool.

The fusion zone from the experiments is triangular, but with lower power ratios it becomes more rectangular. This supports the claim that the trailing spot reaches a depth of fusion similar to that of the main spots when P2/P1 is approximately 65%.

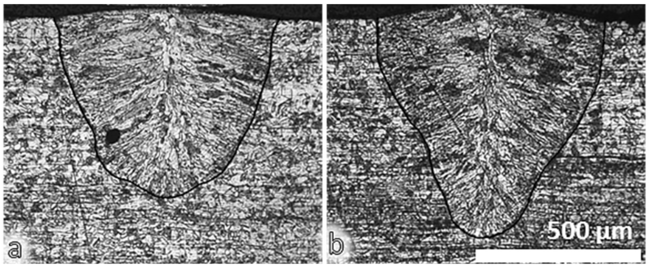

Figure 4 Two cross-sections, both with a = 200 µm, b = 100 µm and P1 = 170 W. a) P2/P1 = 70%, b) P2/P1 = 100%

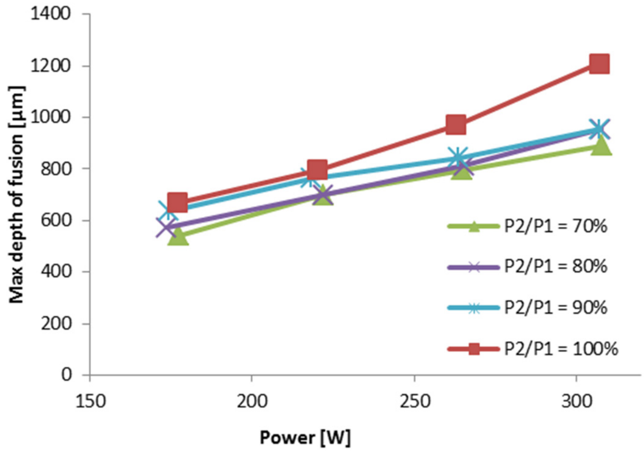

Figure 5 Depth of fusion as a function of power in one of the main spots, P1, for 4 values of P2/P1 with a = 200 µm and b = 100 µm

When the trailing spot distance is increased, the individual solidification lines become distinct in the cross-sections, as shown in figure 6 for b ≥ 400 µm.

In nearly all experiments with b < 400 µm, the trailing spot re-melts the entire weld bead. The power ratio at which the trailing spot penetrates the weld pool is evaluated. The evaluation is performed by examining whether the depth of fusion increases along with the shape change in the weld bead rather than by using distinguished solidification from lines.

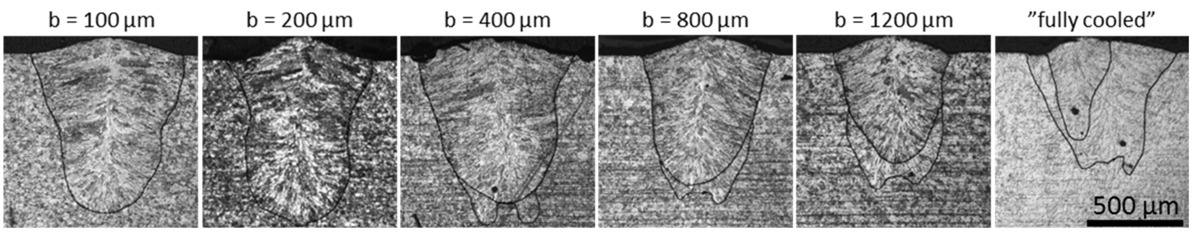

Figure 6 Examples of cross-sections from trailing spot experiments. The solidification lines have been superimposed for increased contrast. b is the trailing spot distance. All experiments in the figure were performed with 260 W per main spot and with P2/P1 = 80%

The graph in figure 7 is based on an evaluation of the cross-sections from trailing spot experiments combined with the knowledge of the depth of fusion for a single spot as a function of power. This shows the tendency that when the distance between the main spots and the trailing spot (b) is increased, the power required in the trailing spot to produce the same depth of fusion increases.

The fact that the power ratio P2/P1 ends at 115% power corresponds with the knowledge that the two main spots affect each other and cause an increased depth of fusion compared to that caused by a single main spot.

The graph is used to design the power ratios for the patterns for the experiments in which parts are polluted with zinc powder.

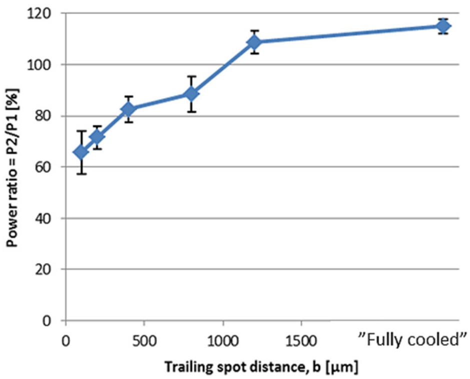

Figure 7 Power ratio needed for achieving same penetration in trailing spots as for main spot. Hansen et al. (2015a)

4.4 Experiments on a butt joint with zinc powder

4.4.1 Experimental setup

Figure 8a shows the setup for experiments on parts similar to those in a real production process; during these experiments, the weld pool was polluted locally with zinc powder: The discs and foil were clamped with a small amount of zinc powder between them. The zinc powder and placement are shown in figure 8b. The discs were set to rotate with a peripheral speed of 50 mm/s, and all welds were performed applying spot patterns with the focus placed 1 mm into the discs (F-1).

The material used for the discs was austenitic stainless steel, EN 1.4301 (AISI 304) with a reduced carbon content of 0.05 %. The chemical composition is given in table 1. The discs were 2.2 mm thick. The centre foil was EN 1.4310 (AISI 301) and 75 µm thick.

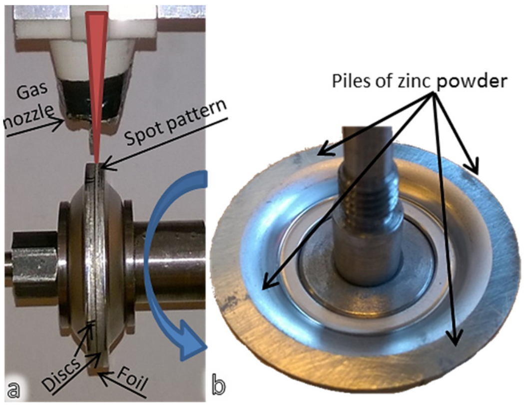

Figure 8 a) Setup and clamping for the second series of experiments. b) Example of disc with placement of 4 small piles of zinc powder

Experiments attempting to determine the best way of depositing zinc powder were performed. The amount of individual grains turned out to be a too small, and electrolytic plated discs with 1-5 µm zinc turned out to be overdosed. Therefore, a final deposition method with small piles of zinc powder was chosen. The amount and placement of zinc powder is not repeatable. In some ways, this reflects the factors of the real world since residues in a production are rarely consistent or predictable. The amount used was exaggerated compared to that which might cause real pollution in production. The exaggerated amount ensured the creation of expulsion of the melt pool during all experiments.

Several different spot pattern designs were tested, ranging from a single round spot to more complicated spot patterns. Figure 9 shows the main types and definitions of distances.

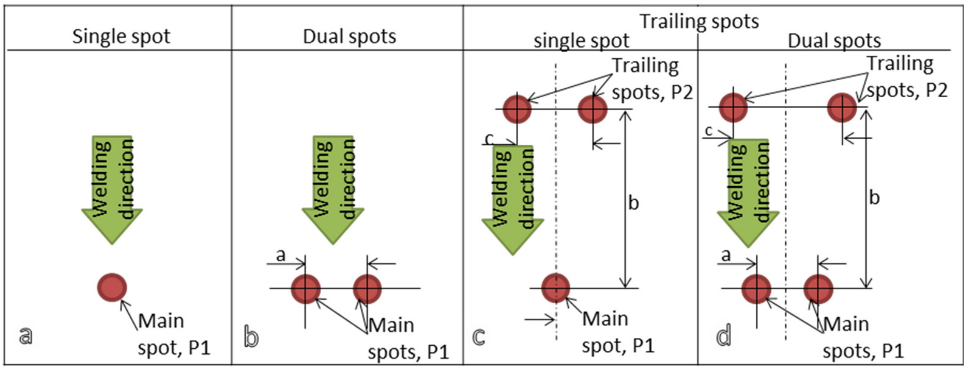

Figure 9 Major types of patterns applied on the production such as parts with and without zinc. c) The pattern is similar to that shown in figure 3, only the welding direction has been reversed.

4.4.2 Single spot

Welds produced with a single round spot, (figure 9a) show sound welds which are sensitive to change of focus position. If focus is lifted, some humping is seen, even at the chosen speed of 50 mm/s, which should be well outside the humping regime. It is possible to achieve neat and stable welds as shown in figure 10a, which was produced with no zinc powder in the interface.

When zinc is present, the weld quality decreases with respect to regularity and smoothness of surface. Results from welding with a single spot and when zinc is present are similar to the cross-sections and surfaces shown for a dual spot pattern, as shown in figure 11c+d.

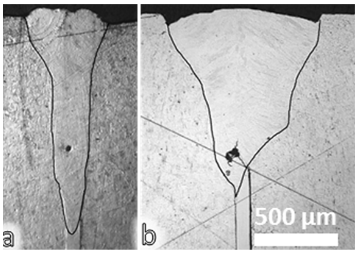

Figure 10 a) Single round spot weld. No zinc was present. b) Results from welding with a single spot followed by a dual spot pattern –zinc was present.

4.4.3 Single spot followed by dual spot

Figure 10b shows a cross-section in which the weld was initially performed with a single spot: Later an extra run with a dual spot pattern (figure 9b with a = 300 µm) was performed.

4.4.4 Dual spots

Figure 11 shows the results from welding with a single run with a dual spot configuration with a = 300 µm. The cross section and surface near the end of the weld zone are shown in figure 11a+b. When no zinc are present, the weld are sound with no pores and good joining of the three parts. The weld showed a slight undercut which was most likely caused by the cross-section being taken close to the end of the weld. When this occurred, the power was instantly turned off, consequently no material was transported backwards in the weld resulting in a slight undercut instead of a weld head. This end-effect can most likely be minimized or avoided by ramping down the power instead of turning it off instantly. When no zinc was present, the surface of the weld was smooth and without holes, pores or undercut. The examined cross sections was also without pores or cracks.

When zinc powder was present, the weld looked as shown in figures 11c and d, in which the melt pool had been completely blown away, causing an unsatisfactory result.

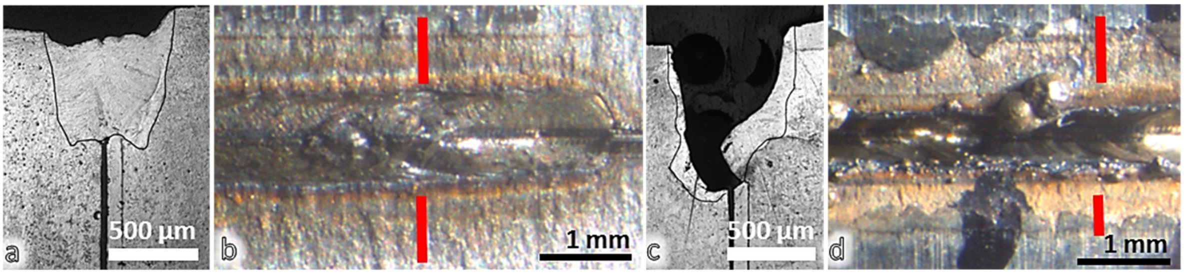

Figure 11 Result from dual spot welding. Red lines indicate of approximate position of corresponding cross-section. a) Cross-section, no zinc was present. b) Surface of cross-section. c) Cross-section, zinc present in weld seam d) Surface of cross section with zinc was present in weld seam. Hansen et al. (2015a)

4.4.5 Single main spot with dual trailing spots

Figure 12 shows the results from welding with the spot pattern shown in figure 9c. The pattern is similar to the one used in the bead on plate experiments with three spots; however, the direction has now been reversed, causing the single spot to act as main spot. The distance between the two trailing spots is a = 200 µm, and the distance between the main spot and the trailing spot is b = 1200 µm. This relatively large distance is employed in order to create some distance from the explosion of the zinc to where the new material is melted.

Cross sections in figures 12a+b+c were performed with P2/P1 = 100%. Several of the cross sections contain solidification cracks originating from the tip of the welds.

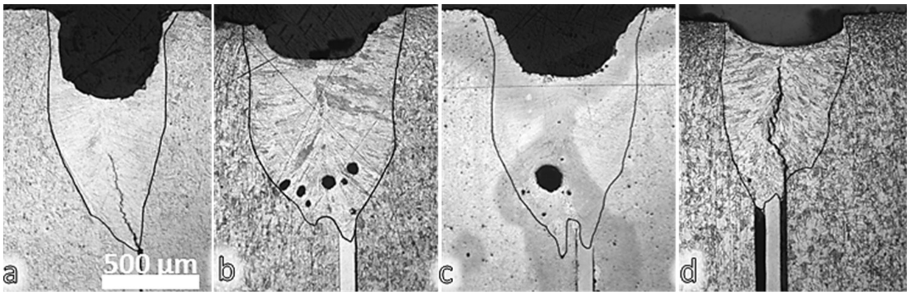

Figure 12 Cross-sections using trailing spots with a distance of 800 µm taken in the middle of the area where the zinc powder is placed. a+b+c) Power ratio P2/P1 = 100. d) P2/P1 = 70%

4.4.6 Dual spots with dual trailing spots

The welds from the experiments with dual trailing spots and a single main spot resulted in very triangular weld beads. A new pattern with two leading spots was therefore designed. The idea was to place a spot on each side of the foil in order to avoid heating the zinc powder directly with the laser spot and to move the keyholes away from the expanding gases and the ejecting melt pool. Trailing spots whose purpose was to widen the weld pool and melt new material were set as trailing spots with power ratios of P2/P1 = 80% and 100%. The principle of the spot pattern can be seen in figure 9c. The results from experiments with a = 200 µm, b = 800 µm, c = 400 µm are shown in figure 13 with a power ratio of P2/P1 = 80%.

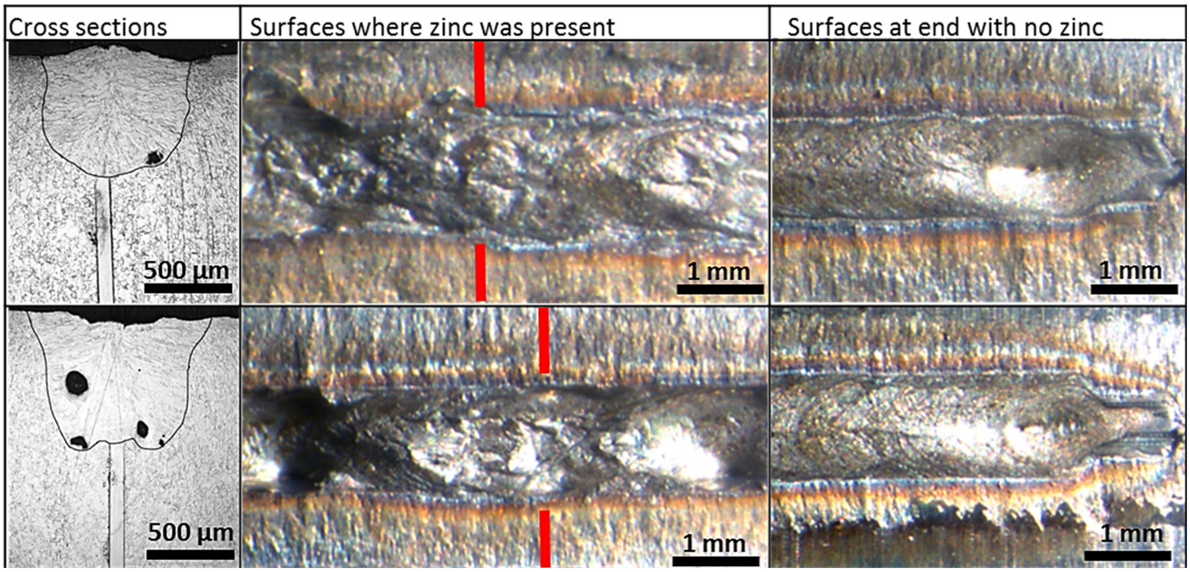

Figure 13 Weld performed with the spot pattern shown in figure 9d. a = 200 µm, b = 800 µm, c = 400 µm, P2/P1 = 80%. A small amount of zinc powder between disc and foil. Middle columns shows surface of weld with indication of approximate position of cross-section to the left. First row from Hansen et al. (2015a)

When no zinc was present, the surface became smooth with no porosities or other weld defects. In the areas where zinc was present, the surface became irregular with some humping. However, the weld surface appeared to have no porosities, cracks or other defects except for the humping and some under filling where the liquid metal is blown away.

5 Discussion

During examination of the welds, different effects were observed, such porosities, cracks and geometric defects.

5.1 Cracks

The welds with a V-shaped cross section have a tendency to form cracks which are initiated at the root and propagated through the weld. Examples of this can be seen in figure 12a. The cracks likely emerge from residual stresses in the weld. In general, the stress situation in a weld is complicated and affected by many other aspects, ranging from micro segregation to thermal expansion and subtraction, this makes it difficult to determine the local residual stresses in the weld without using numerical methods.

In the case of V-shaped welds, the cracks most likely emerge due to uneven solidification during which the tip is the first part to solidify. Initially, the tip of the weld solidifies. Later, when the top surface of the weld bead solidifies, the material retracts, and the tip is exposed to strong tensile tensions in the area where the interface of the foil and discs meet. This interface then initiates the crack.

If the melt pool has a rectangular shape, the crack formation is avoided. In this case, the bottom of the melt pool solidifies more slowly, and the tensile tensions are decreased.

As a general rule, the solidification time at the top of the melt pool and the solidification time at the bottom of the melt pool should be as similar as possible in order for the residual stresses in the weld to be minimized.

5.2 Geometrical defects

The weld in figures 13 where zinc is present, shows highly irregular surfaces with undercut being present. However, the welds do appear to be sound with a limited number of porosities. The surface is also largely improved compared to the alternative shown in figure 11d, in which the foil can be seen and a deep undercut with large irregularities is present.

Since some of the material is ejected from the weld bead, it is difficult to avoid undercut in many of the cross-sections. This may also be seen in the surface photos from experiments during which zinc is present. The undercut is likely to be minimized by adding an extra set of spots with less power in the area where the weld bead meets the solid material. This is similar to what has been presented by Victor et. al., who used two trailing spots to successfully even out the weld toe Victor et al. (2011).

The tested design suffers from the fact that no degassing gap exists; therefore, the vaporized zinc needs to pass through the melt pool. This causes porosities which are not completely removed by the trailing spots. Additional trailing spots will increase the length of the melt pool, which may lead to increased degassing and thus less porosity. However, additional spots will require either additional laser power or a reduction of the welding speed. The welding geometry also needs to be taken into consideration, so that the pattern can be rotated along curvatures with an appropriate radius related to the length of the pattern.

The amount of zinc used in the experiments was heavily exaggerated in order to ensure local expulsion in all experiments. In a real production process, the impurities should be smaller; hence the trailing spot will have "less repair work to perform". This will cause the undercut to be minimized, and the surface irregularities will be reduced as well.

5.3 Porosities

Porosities are present in many of the cross-sections shown. These were caused by the heavy turbulence and the evaporation of zinc; however, this was also seen in a few welds without zinc. It might be possible to avoid these by employing classical countermeasures, such as placing the focus further below the surface, welding with a forward inclined spot pattern or changing the shielding gas used Katayama (2013).

Fully sound welds are made without zinc being present.

In order to ensure full overlap when performing a full weld of the disc, it is necessary to weld a minimum of one round as well as the length of the applied spot. Moreover, laser power should be turned off during a ramp down function, which should be used to minimize the small undercut in the weld bead at the ends as shown in figures 11b, and figure 13 to the right.

6 Conclusion

The inline repair welding of blowouts caused by zinc powder at sheets in a butt joint configuration was performed using various spot patterns.

The initial trailing spot experiments revealed that it is necessary to use 60 – 115% power in a trailing spot if the desired outcome is to be a penetration similar to that seen when welding with a dual spot pattern perpendicular to the weld direction with spacing of 200 µm. If the distance between the main spots is increased so as to ensure that the keyholes in the main spots are not influencing the depth of fusion for each keyhole, the maximum power ratio P2/P1 is expected to drop to 100%.

The results of the study show that applying multi spot LBW can improve the process stability when welding materials with small impurities in the form of zinc particles. Applying the proposed design does not prevent the melt ejection, but in all experiments during which a repair weld was performed, stability was improved and the foil was welded to the discs.

The severe undercuts are difficult to avoid when using the chosen technique which causes expulsion of the entire melt pool.

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