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Mitigation of Laser Keyhole Girth Weld Start/Stop Defects Through Application of Different Laser Termination Regimes

Wai Jun Lai[a]*, Supriyo Ganguly[a], Wojciech Suder[a]

[a] *Welding Engineering and Laser Processing Centre, Cranfield University, Cranfield, MK43 0AL, UK*

Abstract

Laser keyhole initiation and termination defects such as keyhole cavities due to keyhole collapse is a well-known issue in deep penetration laser and hybrid laser welding. Industry can apply such productive manufacturing processes for longitudinal butt welding where run on and off tabs are used to avoid start/stop defects, however, this is not possible for girth weld applications where start/stop defects remain within the workpiece. This study shows that laser keyhole termination defects are more prominent compared to initiation defects in autogenous laser bead-on-plate overlap welding and control of keyhole dynamics is vital to achieve controlled closure of the keyhole during laser termination. Experiments were conducted using two different laser termination regimes at the weld overlap: ramping down of laser power, and gradually increasing the focal distance whilst maintaining a constant laser power output, demonstrating successful keyhole closure could be achieved, eliminating defects associated with abrupt termination of the laser.

Keywords: Laser keyhole welding; Start/stop defects; Laser defocusing; Laser keyhole termination; Keyhole closure

1. Introduction

In laser keyhole welding, the imbalance of keyhole dynamics can cause keyhole instabilities and collapse leading to the formation of porosity and voids throughout the weld, especially during laser termination as demonstrated and explained by Kroos et al. 1993, Zhao et al. 2011 and Courtois et al. 2014. When a laser is suddenly terminated without any control of the process parameters, rapid solidification of the keyhole occurs which leads to an unfilled keyhole cavity at the point of termination. For autogenous laser welding where there is no filler material, the weld is formed solely by the solidification of re-melted parent metal

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* Corresponding author. Tel.: +44 1234 750111
E-mail address: wai-jun.lai@cranfield.ac.uk

alloys which makes filling of the keyhole cavity even more difficult. In longitudinal welds, run on and off plates are commonly used to contain any defects formed during laser start and stops so that they can be removed once the weld has been completed. However, in circumferential welding applications of tubular sections such as pipes, any start/stop defects will remain within the workpiece at the overlap where the weld terminates. Mitigation methods are therefore a necessity to avoid the formation of such defects in laser girth welding applications.

Control of the energy input and keyhole dynamics is important to achieve successful keyhole closure. This has been shown by Narita et al., 1975 in plasma arc welding (PAW) in keyhole mode, where the behavior and dynamics of the keyhole can be likened to that in laser keyhole welding. Keyhole defects are more significant at termination points where the sudden termination of the arc can lead to keyhole instability and collapse or rapid solidification of the keyhole, leaving behind a keyhole cavity. Wang et al., 2006 has demonstrated that successful keyhole closure can be achieved when terminating the arc in both longitudinal overlap and girth welds through control of the keyhole dynamics by reducing both the plasma gas flow rate and weld speed.

In laser girth welding applications, the most common procedure for keyhole closure can be achieved by ramping down of the laser power to gradually reduce the weld penetration as explained by Dawes, 1992. However, keyhole instabilities and overlap welding can lead to the formation of porosity. In hybrid laser arc welding, Reutzel et al., 2007 observed porosity and blow-through at weld start and ends due to laser keyhole instabilities. The authors found that the use of laser power ramping can be used to control penetration and blow-through at the start/stops but further studies to mitigate porosity formation was required. Similar mitigation methods of laser start/stop defects can be seen in the pipe cladding industry. Ocelík et al., 2012 applied two successful methods at the start/stop intersection, both of which reduces the laser power density by either: reducing the laser power; or by increasing the laser beam spot size as it reaches the termination point. These methods gave uniform material properties throughout the start/stop intersection.

In this study, the causes of start/stop defects and the possible methods of eliminating them were investigated. Controlled experimentation on flat plates were carried out to demonstrate the possible methods of minimising the formation and significance of laser termination associated defects. Girth welding process principles were simulated on bead-on-plate configuration on flat plates, creating a specific overlap distance as observed between start and stop points in a circumferential weld.

2. Experimental procedure

The experiments were carried out using an 8 kW maximum output IPG CW fibre laser with a fibre diameter of 0.3 mm, collimation lens with focal length of 125 mm and a focusing lens with focal length of 250 mm. This setup gave a focal point laser beam spot diameter of 0.6 mm. Autogenous laser bead-on-plate welds were carried out on commercially available S355 low carbon structural steel plates of dimensions 300

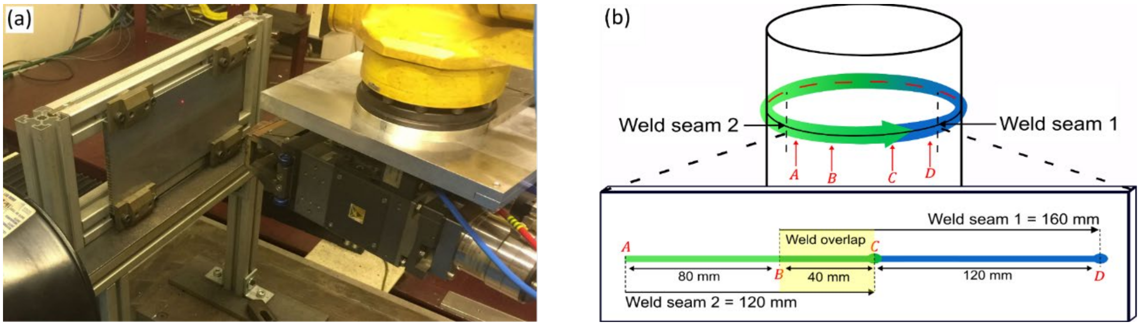

Fig. 1. (a) Experimental setup, (b) schematic of girth weld simulated onto a flat plate

mm x 120 mm x 8 mm. The plates were machined to remove mill scale, cleaned with acetone and clamped horizontally in place in the 2G welding position as shown in Fig. 1 (a). All welds were carried out with the focal point on the plate surface without shielding gas to minimise any interaction with the gas plume and with the laser head tilted by 10° opposite to the welding direction to avoid back reflection.

X-ray radiography was carried out from above the welded plates so that any defects at weld start/stops and weld overlaps could be identified. Weld samples of the weld overlap from all plates were cut longitudinally, polished and etched using 2 % Nital solution and macrographs were taken to reveal the weld profile.

2.1. Simulated girth weld on flat plate by overlap welding

Girth welds were simulated onto flat plates by applying the same procedure as Wang et al., 2006 and Reutzel et al., 2007 as shown in Fig. 1 (b). Each point denoted as A, B, C and D represents the two initiation points (A and B) and two termination points (C and D) of the two bead-on-plate welds respectively. The length of each weld seam is shown in Fig. 1 (b) giving a total weld length of 240 mm so that the start and end points of the welds are 30 mm away from the plate edge. Three separate weld cases were simulated on each plate. Each weld seam pertaining to a weld case was kept 30 mm apart from another to avoid any overlap of the heat affected zones. After welding the 1st weld seam (from point B to point D), the plate was left to cool to room temperature before the 2nd weld (from point A to point C) took place to negate the effect of any inter-pass temperature on the weld start/stops and also to simulate the scenario in girth welds of large outer diameter pipes typically used in the renewable energy sector. Laser power ramp down and laser defocusing termination regimes were applied during the overlap of the welds from point B to point C, over a 40 mm distance. The intentionally elongated overlap weld allows the initiation and termination points of a simulated girth weld; points *B* and *C,* to be studied separately.

2.2. Parameters and termination regimes

Weld parameters were selected from a series of trial welds which provided full penetration with uniform top and root surface quality based on visual inspection. This resulted in a laser power of 3.79 kW and weld speed of 0.5 m/min which were used nominally for all welds except for the changes that were applied during the termination regime at the weld overlap. Both termination regimes reduce the laser power density, P_d, either through the reduction of laser power, P, or through the increase of the laser beam spot size, $Ø$ as equation 1 shows.

$$P_d = \frac{P}{Ø^2} \qquad (1)$$

The laser power ramp down regime consists of a linear reduction of laser power from full power at point B to the set termination power at point C for each weld case. The laser defocusing regime consists of a linear increase of focal distance from point B to point C by traversing the laser as shown in Fig. 2. This increase in focal distance leads to an increase in the laser beam spot size. The parameters used for the two termination regimes and the calculated power density at each termination point for each weld case are shown in Table 1.

Table 1. Termination regime parameters

Termination regime	Termination power (kW)	End beam diameter (mm)	Power density (kW/cm²)
Laser power ramp down	1, 0.5, 0	0.6	353.7, 176.8, 0

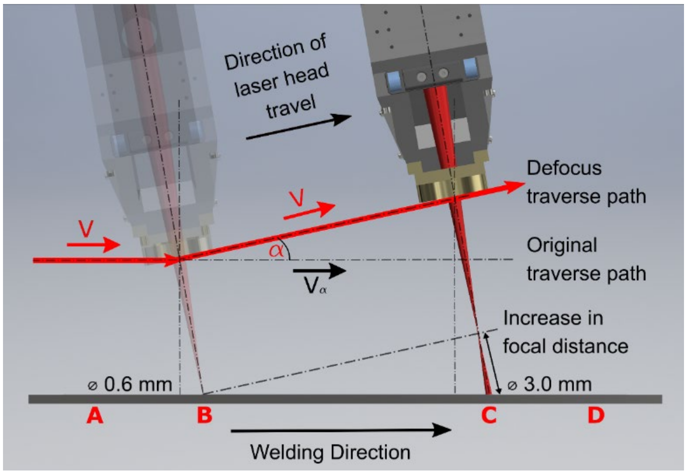

Fig. 2. Schematic of laser traverse during laser defocusing termination regime

Laser defocusing	3.79	1.8, 3.0, 4.2	148.9, 53.6, 27.4

3. Results and discussion

Photos of the weld bead surface and x-ray radiography results of the welded plates are shown in Fig. 3. Though the material is not normally susceptible to cracking; as it has good weldability, solidification cracking can be seen just after where the 2nd weld seam starts (point A) as shown between the two red dashed lines in Fig. 3. The crack forms due to the thermal stresses during solidification caused by the high cooling rate of

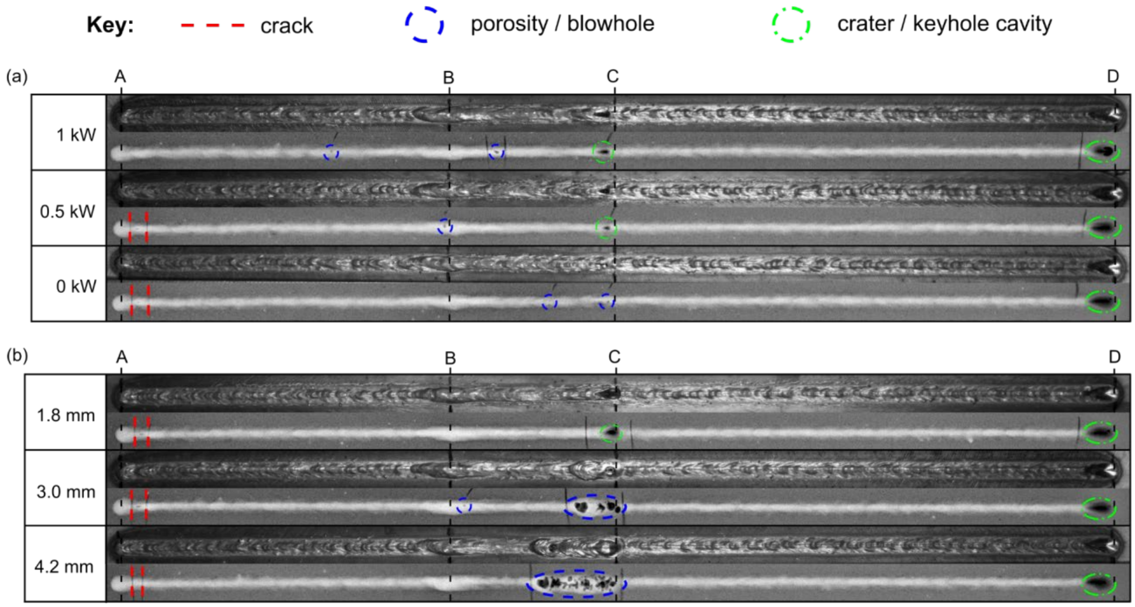

Fig. 3. Bead surface and X-ray radiograph of; (a) laser power ramp down welds, (b) laser defocusing welds

the laser weld process and surrounding parent metal. Typically, the initiation of a laser weld can be controlled by gradually ramping up the laser power to slowly heat up the material and form the laser keyhole to avoid overheating which would also reduce the high cooling rate experienced at the start of these welds however this was not applied for these experiments. At point B, where the start of the 1st weld seam is overlapped, no cracking is evident unlike at point A (note that point B should be identical to point A if it was not overlapped) however there is instances of porosity within this region. This shows that laser keyhole initiation defects; like the cracking observed at point A in Fig. 3, can be remedied when the start point is overlapped even if no control is applied during laser initiation such as gradually ramping up the laser power as previously discussed.

Laser keyhole termination on the other hand is always susceptible to defect formation such as an unfilled keyhole cavity unless a suitable termination regime is applied to fill the keyhole cavity at the end of a girth welding process. An unfilled keyhole cavity can be seen at the termination point D in Fig. 3 circled by the green dot-dashed line where the laser was terminated at full power. These results show that the start/stop defects are more likely to occur due to the abrupt termination of the laser rather than the laser initiation. Keyhole dynamics appears to be the most dominant in the formation of laser weld termination defects.

When laser power ramp down is applied from point B to point C, a linear reduction of laser power density occurs which leads to a gradual reduction in the penetration depth depending on the rate of the laser power ramp down and termination power as shown in Fig. 4 (a). The presence of small crater remains when the laser power is ramped down and terminated at 1 kW and 0.5 kW, which indicates that there is insufficient weld material to fill the melt pool during solidification. When the laser power is ramped down to 0 kW, successful keyhole closure is achieved however, the presence of a small pore remains at the point of laser termination which suggests that solidification of the melt pool occurred before any dissolved gases or vapour could escape. It is also evident from Fig. 4 (a) that the weld bead width narrows when laser power is ramped down due to the reduction heat input applied and change in cooling rate which will affect the weld profile and lead to a gradient of microstructure along the weld overlap. This will have a potential effect on the mechanical properties at the weld overlap which will require further studies.

When laser defocusing termination regime is applied, a different behavior of the solidification pattern was observed. By controlling the laser beam spot size through the overlapped length, a stable and gradual

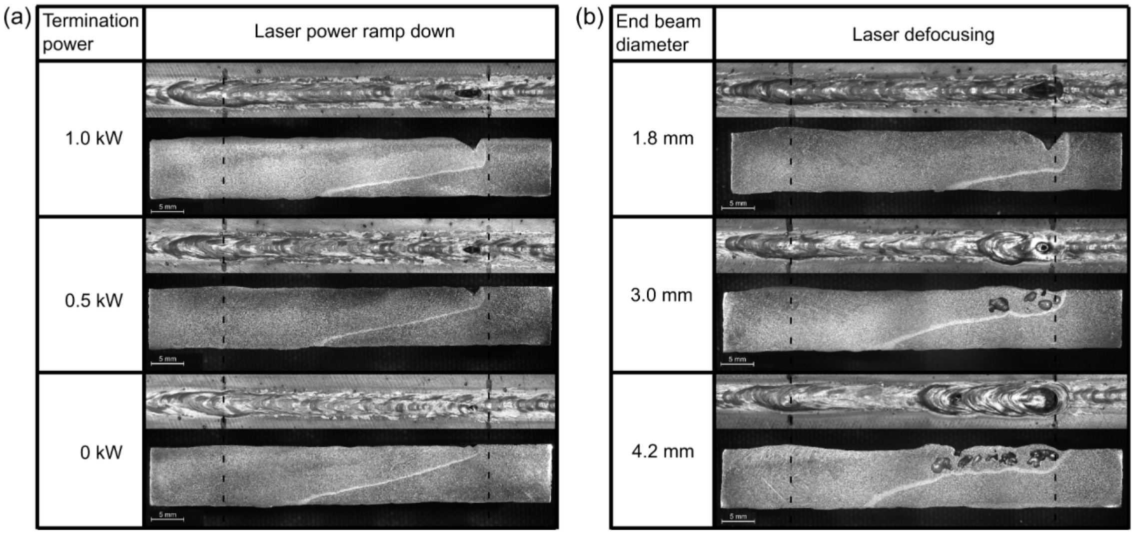

Fig. 4. Bead surface and longitudinal macrographs of weld overlap of; (a) laser power ramp down welds, (b) laser defocusing welds

transition from keyhole mode laser welding towards conduction mode is possible due to the reduction of power density whilst maintaining a constant laser power and therefore heat input. As can be seen in Fig. 4 (b) the bead width at the weld overlap increases due to the increase in laser beam spot size which is opposite to the previous study. This increase in bead width means that there is more molten parent metal which helps with the filling of a keyhole. This change in weld bead profile will also impact the mechanical properties as previously mentioned. Another difference is that the distance from point B at which the weld leaves full penetration varies more significantly in laser defocusing to that of laser power ramp down. This is due to the greater initial reduction in the laser power density (which can be correlated with the penetration depth) when the beam spot size is increased compared to reducing the laser power. When defocusing to an end laser beam diameter of 1.8 mm, the power density is still high so material vapourisation still occurs leaving a large and deep keyhole cavity upon laser termination. Defocusing to an end laser beam diameter of 3 mm and above leads to successful keyhole closure due to a greater reduction in power density however, the presence of porosity clusters or blowholes can be seen in both the x-ray radiography in Fig.3 (b) and longitudinal macro in Fig. 4 (b). Though the keyhole cavity has been successfully filled, the occurrence of such defects is not acceptable. The formation of these porosity clusters or blowholes can be explained by the enlarged melt pool due to the increased laser beam spot size which leads to more gas entrapment as the solubility of gases rises with higher temperature. The dissolved gases in the melt pool would increase and migrate towards the centre of the melt pool where the temperature is higher as the power distribution is now more Gaussian due to the defocused laser beam but once the melt pool begins to cool, the dissolved gases cannot withstand the metallostatic pressure any further and escape which leads them being entrapped as porosity. Another cause can be due to the lack of shielding gas used in these experiments which can also lead to this type of porosity. Follow up experiments will need to be conducted to determine whether the lack of shielding gas is the cause of these defects and methods of remedy.

4. Summary and outlook

In this paper, mitigation of laser keyhole start/stop defects in autogenous laser bead-on-plate girth welds simulated onto flat plates using two different laser termination regimes were studied.

Start/stop defects in autogenous laser bead-on-plate girth welds (overlap welds) in keyhole mode are likely to occur due to the termination of the laser beam rather than the laser initiation itself. This is because of the abrupt termination of the laser beam leading to keyhole instabilities and subsequently, keyhole collapse which can leave craters and unfilled keyhole cavities in the workpiece. Laser keyhole initiation defects are not as severe in girth welds when compared to longitudinal welds as they can be mitigated when the start point is re-welded by the overlapping weld even if no control is applied during laser initiation such as gradually ramping up the laser power.

The application of either laser power ramp down or laser defocusing termination regimes for keyhole closure has been shown to be successful in mitigating laser termination defects associated with the abrupt termination of the laser source. Laser defocusing gives another alternative for laser termination other than the more commonly applied ramp down of laser power, allowing for more flexibility and control of the thermal cycle and melt pool dynamics. Both termination regimes reduce the laser power density, but the heat input applied is different as previously mentioned. Further experiments on other strategies such as combined laser power ramp down with linear defocusing will be studied in the future.

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