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Effects of welding parameters onto keyhole geometry for partial penetration laser welding

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Abstract

The material and parameters like welding speed and laser beam parameters define the geometry of the keyhole. The keyhole geometry affects the weld geometry, such as width and depth, and in some cases it should be considered when selecting welding parameters. In-situ X-ray videography makes it possible to obtain time-and space resolved information about the keyhole geometry during the welding process. This paper describes the partial penetration laser welding experiments and shows the effects of a welding speed and a focal point position change onto some geometry values of the keyhole. Two different joint types were used, bead on plate to simulate a very good machined joint preparation and laser cut I-butt joint.

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1. Introduction

Previous experiments have shown that welding parameter selection can have a great impact on weld shape [1, 2]. For example high welding speed can form, in case of copper welding, a droplet-shaped weld having a so called “big bubble” below the top surface even if the weld seam on the surface is narrow [1]. The joint edge roughness also can have an effect on the penetration, the optimal edge roughness can be used to increase weld penetration depth without increase in laser power [2]. The x-ray imaging during laser welding itself is a well-established method to examine the keyhole behaviour with side view through the material. First experiments were published by Arata et al. during 1985 [3, 4]. Since then the brightness of the micro focus x-ray sources has significantly improved resulting much higher image quality. Image capturing has become faster and maximum possible sample width has increased, which means the thickness the x-rays must penetrate. Katayama’s group has studied the x-ray videography widely with the emphasis on analysis of pore formation

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and melt flow [5]. The keyhole has been observed with many different space and time resolved methods, for example with high speed imaging from top side [6]. However, the keyhole geometry inside steel is only visible with x-ray videography. There are some x-ray videography results, but parameter range has been small and only limited joint types. Naito et al. [xx] showed YAG-laser welding of stainless steel type 304 with x-ray visualised keyhole during the process. The main focus area of their study was to track melt flow during YAG-laser and TIG-YAG-hybrid welding. The melt flow was visible, but the keyhole geometry was not fully visible [7]. In 2009 Zhang et al. compared keyhole depth to weld depth; they used image averaging of x-ray images in the study to achieve better contrast of the keyhole. The material was mild steel and the laser was a 7 kW fiber laser. The main focuses of this study were the influence of the shielding gas and surface tension [8]. Weberpals et al. studied Nd:YAG-laser welding of thin stainless steel. They showed that capillary front inclination angle to laser beam optical axis increases with increase in the welding speed [9].

The motivation for this work was to study what is the keyhole geometry like when different welding parameter values in different joint geometries are used and to observe the differences between bead on plate and butt joint welding. The keyhole geometry was visible by x-ray videography with all the test samples. Bead on plate welding can be compared to a good quality machined edge and to a self steering joint in tube to tube welding. This means that the tube ends are machined into a cone shapes such that they fit together and when a pressure is added longitudinally to tubes the cones are pressed together forming a tight joint [10].

2. Experimental

Designing fixtures for X-ray investigation is a challenging task: due to the limits in X-ray power [11], the transmitted thickness of the samples has to be less than about 10 mm while maintaining the joint properties under investigation. Figure 1 shows partial penetration fixture and the partial penetration butt joint. Also partial penetration bead on plate was tested, but it is fully solid material without a joint. All of the samples were laser cut austenitic stainless steel of EN 1.4404. The thickness was 8 mm and the width of the sample at welding position was 6 mm through which the x-ray must penetrate. This means that bead on plate samples were 6 mm wide and each butt joint sample 3 mm wide and 6 mm total width of two samples. The welding speed was varied from 2 to 5 m/min in 1 m/min steps and focal point positions from +2 down to -6 mm mainly in 2 mm steps, minus being below the sample top surface. The weld set was designed to provide information from large parameter scale to show the differences in the keyhole geometry.

Fig. 1. Partial penetration fixture and welded butt joint sample in the work station on left and partial penetration butt joint fixture on right and the corresponding joint types.
The main component in the X-ray imaging system is a micro-focus X-ray tube. The minimum spot size of the x-ray beam with this tube is 6 μm. Typically used spot sizes are in the range of 50 to 150 μm, depending on the used tube current which is affected by the frame rate of the high speed camera, the sample material and thickness. The acceleration voltage can be between 10 kV and 225 kV with a maximum current of 3 mA [11, 12, 13].

The sample is projected onto a scintillator plate being the first part in the imaging system. The magnification depends on the sample distance to the x-ray tube and the scintillator. The scintillator converts the X-rays into visible light and this light is directed to an image intensifier by an optical system. The image intensifier converts the visible light into electrons that are multiplied in a micro channel plate and a booster and after multiplying is converted again into visible light. This intensified image is focused by a lens onto the camera chip of the high-speed camera [11, 12, 13].

The keyhole depths were measured from averaged x-ray images. The average images were made by a program from the x-ray videos, the used weld length was approximately 70 % the whole weld. The program calculates average intensity values for each pixel of each single frame and then forms a single image which shows average intensity image of the process. The amount of total images included in the program calculations was from 400 up to 1600 images, depending on the welding speed. In the averaging process the image becomes much clearer and contrast is greater than in a single frame in the video, but it must be taken into account always that it is an average geometry of the keyhole from the major part of the weld. Also shading process is used to remove imaging errors and possible spatter on the shielding plates. Shading means that first an average is taken from even object and then raw x-ray video is divided by this average of the even object to remove these flaws in the system [14]. Image averaging process removes high oscillations and spiking if there is some. Spiking and large oscillations must be found from the videos separately.

All of the welding experiments were also videographed using a high speed camera with a filter that only allows a certain wavelength range to pass through. It was used with a continuous wave illumination laser that illuminates the work area and this light passes through the filter into the high speed camera. This method reduces greatly the effect of almost white light emitted by the laser welding process itself. This allows seeing what happens below the plasma cloud in the process such as the keyhole opening and a melt pool. There are some minor drawbacks in this method; if the melt pool edge or surface is in a certain angle the illumination laser light is reflected from the mirror like melt and this very bright spot is blurring the view of the video.

3. Results and Discussion

Figure 2 shows keyhole depths of partial penetration bead on plate and also butt joint welds. The variation of the keyhole depth is approximately 6 %, which comes from pixel to mm calculations and oscillations of the keyhole which was visually measured from 40 ms averages and x-ray videos.
The beam diameter and intensity at the surface is not the only affecting issue in the keyhole depth, also the focal point position affects. In the case of bead on plate welding at 2 m/min the penetration depth first increases when changing from +2 to 0 focal point position, this change reduces the spot size on the surface. When the focal point position is lowered below the surface resulting in the same beam diameter at the surface than +2 focal point position, the penetration depth is still increased. Lowering the focal point position even more below the surface starts to reduce the penetration depth but in case of the focal point position of -5 mm, the beam diameter is more than doubled from the focal point position on the surface, but the penetration depth is about
the same at the speed of 2 m/min. Another main measurement is the difference between weld versus keyhole depth at different beam diameters and welding speeds, as shown in Figure 2 b) and d) graphs. The difference change is relatively large in single experiments, but the average stays at +127 % of the keyhole depth with bead on plate and +122 % of the keyhole with butt joint. Figure 2 b clearly shows that increase in weld depth is higher with slower welding speed and drops considerably after beam diameter is more than two times the focal point diameter. The change of welding speed from 2 and 5 m/min is causing considerable difference in weld penetration due to shallower keyhole followed with shallower weld penetration. This causes the increase of weld penetration depth compared to keyhole, in mm scale, to be smaller at higher welding speeds, but the fraction of depth differences between keyhole and weld penetration is roughly the same in both cases. With butt joint the difference has more variations, but comparison between different welding speeds shows very similar increase. At 0 down to -4 mm focal point position resulted in deepest penetration in general. At higher welding speeds the deepest penetration was achieved with the focal point on the surface but with slower welding speed the deepest penetration was achieved with focal point below the surface.

Lowering the focal point position also changes the beam geometry inside the sample together with change in beam diameter on the surface. This also has an effect, mainly on the keyhole geometry as shown in Figure 3, which shows five welds with 2 m/min and 5 kW laser power with different focal point positions. The beam diameter at the surface is changing from 0.29 mm to 0.73 mm according to the focal point position. The beam divergence half angle is 4.09 degrees, marked in the figures. The measurement on the left ranging from 2 mm above the surface on far left in Figure 3 and down to -5 mm below the surface on far right on Figure 3 marks the location of the focal point position. The keyhole depth is also marked on right side of the keyhole in each figure. Front inclination angle of the keyhole is also in the figures. The white lines through the whole image marks the laser beam in each figure. Centre line of the laser beam and also the divergence is shown.
Fig. 3. Keyhole geometry changes depending on the focal point position. All welds had 2 m/min and 5 kW laser power, but the focal point position changed. Here also the +2 and -2 focal point position real diameter at the sample surface was 0.39 mm. Lower images are the weld cross sections in the same order. Keyhole traverse direction is to the right and the melt pool and the weld is on the left side of the keyhole. Melt pool front bubble is also visible in the figures as a dark half circle above the surface in the x-ray images. It is the highest with focal point on the surface in second image.

With equal energy input the keyhole geometry changes according to the focal point position, but the depth of the penetration is close to the same in each weld, except at +2 mm the penetration is noticeably lower. The highest penetration with 2 m/min was achieved with -2 focal point position. The lighter area behind the keyhole is so called shrinkage, which means that the sample width has changed due to upward movement of molten metal. This causes smaller depth which the x-ray must penetrate and is visible as lighter area behind the keyhole, where the melt pool is and where the weld is formed, left side of the x-ray image. The differences between the focal point position of +2 mm and -2 mm in keyhole geometry are caused by the beam focusing angle direction. With +2 mm position the beam divergence is outwards, but with -2 mm position the direction is inwards at the sample surface. This can be seen from the geometry of the keyhole. In the case of +2 mm position the keyhole is shallower and the diameter of the keyhole reduces as a function of the depth. In the case of -2 mm position the keyhole reduces in diameter down to -1.5 mm and then stays the same until the last 10 % of the depth. The weld geometry also changes according to keyhole geometry and so according to the
parameter settings. When the focal point position is above the surface the weld is shallower, but slightly wider at the top. When the focal point is lowered inside the material the upper large area of the weld is smaller and the weld geometry is according to the light trap form of the keyhole. The weld surface and fusion zone is wider due to different heat conduction at the sample surface when compared to heat transfer inside the material.

As shown earlier, the keyhole depth has increased considerably when there is a butt joint with high welding speed. At low welding speeds the keyhole penetration is very close in both bead on plate and butt joint welding even with the large bevel on the top edges of the samples. The main cause of deeper penetration at 4 and 5 m/min welding speeds was the bevel of the edges. This increase in penetration depth also depends on the focal point position (focal point diameter at the surface). With high welding speed and optimum focal point position, which was 0 to -4 mm below the surface depending on the welding speed, melt pool top is inside the joint and does not melt sufficient amount of material on top edges and there is no time for the melt to fill the gap from the bottom part of the melt pool to form sufficient weld bead reinforcement. Figure 4 shows two examples of visual high speed imaging a) where the melt pool top goes into the joint, below the sample surface, and on the other b) stays on the sample surface.

![Figure 4](image_url)

**Fig. 4.** Two welds, upper with 5 m/min and -2 focal point position and lower with 2 m/min and -2 focal point position. Red circles points the locations in which on a) there is no melt on the surface but b) there is melt visible on the image. Keyhole traverse direction is to the right in both x-ray and visual images.

The increased penetration effect caused by the bevel affects only at high welding speeds and with this effect the penetration depth difference between bead on plate and butt joint is at highest. This type of butt joint was used to simulate orbital solid state laser cutting of stainless steel tubes and the resulting edge quality in a study made by the main author [15]. The largest differences in penetration without underfilling were with 2 and 3 m/min welding speeds. When the focal point position was deep inside the sample the difference was also large. The parameter window is relatively small in which the results are comparable, meaning that there is no
underfilling, and there is a noticeable difference. Slow welding speed did not induce real differences in the penetration of the keyhole and with high welding speed the melt pool top side goes inside the bevel and this increases penetration. In this case the keyhole opening is not clearly visible due to beam induced plasma light leakage through the optical filter of the camera.

Figure 5 shows bead on plate welds with same laser power and welding speed but different focal point positions. The keyhole front angle changes considerably depending on the welding speed and also by the focal point position, beam diameter and intensity on the sample surface. Both of these parameters have a great effect on the keyhole and both needs to be taken into account to achieve desired keyhole geometry and finally desired weld geometry. In cylinder shape keyhole which has very flat bottom, but the angle of the keyhole causes the beam to reflect more to the backside on the bottom half of the keyhole rather than deeper into the material. The effect is not like light trap, which is the most common type of reflection mode in a common keyhole. The angle of the cone shape keyhole usually changes according to the welding speed and the higher the speed the more the root of the keyhole bends backwards.

![Figure 5](image)

Fig. 5. Laser power 5kW, welding speed 5 m/min welds with different focal point positions, due to beam dispersion the focal point diameter can be slightly different. At -2 mm position the real beam diameter is 0.39 mm. Lower images are weld images shown in the same order.

The lower intensity and the larger beam diameter at the surface the weld becomes cylinder shape and very shallow. In addition to change in keyhole geometry, the oscillations in the depth and geometry are larger compared to keyholes with normal geometry at focal point positions of -2 and -4 mm. In Figure 6 keyhole front inclination angles are shown for both joint types. Keyhole front inclination angle changes reflection type from “light trap” mode at slow speed or optimal focal point position to cylinder mode at high speed and certain focal point position. In this cylinder mode the “light trap” is more like a bubble and it forms on the backside on the bottom of the keyhole.
Fig. 6. Keyhole front inclination angles for a) bead on plate and b) butt joint.

Keyhole inclination angle with bead on plate is quite linear and increases steadily when welding speed increases but especially when beam diameter at the surface increases. The same effect is not as clear with butt joint, but the keyhole acts differently due to the bevel in top parts of the joint edges. It is visible that the angle mainly increases with increase in beam diameter. Butt joint welding is very dependent on the joint edge quality and possible bevel affects greatly.

4. Conclusions

The joint affects considerably on the keyhole geometry especially when there is a bevel. Bead on plate is comparable to a good machined butt joint which is a common method in industry as well as laser cutting. The parameter window to achieve acceptable weld for these two types of joints can vary greatly. Bead on plate can also be compared to a self steering joint in tube to tube joints which was studied by the main author. Using a laser cut butt joint can result in deeper keyhole penetration but also different geometry of the keyhole and the weld. Laser cut butt joint used in these experiments had a small bevel in top of it. The main issue is the bevel which has to be taken into account due to changes in the keyhole depth and increased possibility of underfilling. Large beam diameter on top of the work piece helps to achieve acceptable weld with the bevel due to fully melting edges of the sample. In any case the process requires time to fill the bevel from the melt pool to achieve sufficient bead reinforcement.

The keyhole can have cylinder shape, in which the light trap effect is tilted and it forms a large, but shallow, vapour cavity behind the beam centreline. This reduces penetration greatly and forms a weld that is more even in width the whole depth. With all parameters it is possible to control not only penetration but also weld shape with the focal point position. The ratio between weld and keyhole stays almost the same independent of the beam diameter with both bead on plate and also with butt joint. The average ratio of weld and keyhole is 127 % with bead on plate and 122 % with butt joint. This is a considerable increase in the weld depth comparing to keyhole depth, but average increase was only slightly higher with bead on plate. This means that average bead on plate melt is deeper compared to butt joint.

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