Melt pool forming a buttonhole in tailored blank welding with multiple laser spots

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Abstract. Laser beam welding of tailored blank butt joints of different sheet thickness generates asymmetric melt pool conditions. By employing two, three or four tailored laser beams, additional options for shaping the melt pool conditions can be offered. As observed by high speed imaging, in most multi-spot cases a large stable buttonhole was generated, by the trailing laser beams asymmetrically towards the thinner sheet. Correspondingly, the ablation pressure from the multiple boiling fronts has generated a fast melt jet, particularly along the thicker sheet. In many cases the boiling front kept open to the keyhole rear. The buttonhole differs from the Catenoid-like shape reported earlier. The walls are steeper and the horizontal shape can be asymmetric. The melt pool can switch between different stable modes. Inclined arrangement of three beams enabled even two separate, parallel boiling fronts and melt jets, combining behind the opening. Despite the large buttonhole, sound welds were achieved. Solely for four equal laser beams, arranged as a square, a melt pool without buttonhole was generated. Provided the driving forces from the ablation pressure along with the melt flow are sufficiently explored and understood, new opportunities to optimize the welding process are available.

1. Introduction
In welding processes, the melt pool is the essential central domain determining the energy transfer as well as many aspects of the final quality of the welded joint. For given extension from heat conduction, the shape of the weld pool is governed by the melt flow resulting from the driving forces and the counteracting surface tension forces. In keyhole laser welding of thin sheets, a few authors [1-4] have reported the occurrence of a so-called buttonhole, a hole in the pool much larger than the keyhole that keeps open during the quasi-steady-state welding process because the hole boundary forms a Catenoid-like shape. The Laplace pressure contributions of the vertical and horizontal directions cancel each other out. The adequate Young-Laplace equation writes:

\[ p_L = \gamma \frac{1}{R_V} + \gamma \frac{1}{R_H} \]  

where \( p_L \) is the resulting surface pressure, \( \gamma \) the surface tension, \( R_V \) and \( R_H \) the surface curvatures in the vertical and horizontal coordinate, respectively. Non-circular elongated holes with a length-to-width aspect ratio of up to four were observed by high speed imaging of laser welding of thin (0.5 to 2.1 mm)
sheet aluminium [5,6] or mild steel [6], which has led to a calmer process for the mode of elongated holes, as was supported by calculations on the Laplace pressure.

In the most common keyhole laser welding processes, the laser beam forms a quasi-steady keyhole, either of full or partial penetration. The melt passes around it either horizontally or underneath. The convective heat transfer generates an elongated melt pool. The melt pool shape just at the solidification interface determines the resulting weld quality, which can include reinforcement, undercuts or underfill as well as imperfections like porosity, hot-cracking or lack of fusion. Underfill can be promoted by root drop-out or spatter. For deeper understanding of the melt pool flow, experimental high speed imaging observations, HSI, and computational fluid dynamics simulation, CFD [7,8], are suitable methods. Already early CFD simulations as well as semi-analytical models explained how the melt can be horizontally redirected around the keyhole, similar to a cylindrical obstacle, through the laser-induced ablation pressure from boiling at the leading keyhole front. This can even cause strong melt pool jets in the wake of the keyhole. It can be kept in mind that strongly accelerated melt is accompanied by a thinner cross section according to the conservation of mass, as well as by a drop in static pressure, from conservation of momentum – and vice versa when slowing down in the tail or against surface tension forces. In contrast to the self-regulating front wall, the rear wall of the keyhole results from less controlled mechanisms, which are less understood yet, like the forces from the vapour jet against surface tension [9], but also complex additional jets, as more recent sophisticated CFD-simulations show [7,8].

From high speed imaging of the keyhole front at 180 000 fps for fibre laser welding of stainless steel, waves were observed that travel down the front [10]. The melt speed, in the range of 4-18 m/s, increased linearly with the laser power. This confirms the likely occurrence of root spatter for full penetration keyhole welding as well as the favoured melt flow route underneath rather than around the keyhole [11], which can under certain circumstances like high welding speed lead to humping. Mathematical modelling of the absorption of a laser beam at a wavy keyhole front [12] indicated for near infrared lasers (NIR, here 800-1100 nm) the favoured amplification of surface waves, explained by the angle-dependent Fresnel-absorption, while the longer CO2-laser wavelength (10.6 μm) theoretically does not support the amplification. For fibre laser processing (remote cutting) of aluminium, the authors recently observed that no regular waves were formed. However, for NIR-lasers and steel the presence of the waves down the keyhole front was meanwhile confirmed for many different conditions. Typically the melt pool at the top surface during keyhole laser welding looks quite similar at the root, while CFD-simulations [7] have shown that the tail can be much shorter inside the material, by lack of the convective surface flow to the rear side. Marangoni convection is often only a minor melt flow contribution during laser welding, although present. Instead, the ablation pressure used to be the main driving force.

Butt joints of two sheets with different thickness are usually joined during tailored blank welding, as semi-finished parts particularly for the automotive industry. Welding sheets of equal thickness but different steel grades is also denominated tailored blanks. This study focuses on different thickness, causing the interesting aspect of laterally asymmetric melt pool and keyhole conditions. In particular, the shape of the weld cap from the thicker to the thinner sheet can be optimized, normally placing the step on top while the bottom surfaces are levelled out. Although numerous studies on tailored blank laser welding (TBLW) have been published [13], the melt pool for these asymmetric conditions was hardly studied in depth, neither by HSI nor by CFD. For process monitoring [14], a few photographs are provided that indicate the asymmetric melt pool. The temperature field was recently calculated [15] by finite element analysis, FEA, for TBLW with a dual beam, rotated 45° and 90° to the welding direction.

Laser welding with two laser spots has been occasionally studied. CFD-simulation of the melt pool during tandem welding [16-18] showed for different spot distances how the second beam contributes through a step in the melt profile to a combined, elongated keyhole development. For large distances the keyholes are gradually separated through a melt wall. Certain keyhole locations can experience overheating and violent evaporation events, supporting a transient behaviour [18]. More than two laser beams were seldom studied. The seam cross section from laser keyhole welding was shaped for up to five beam spots lined up perpendicular to the welding direction [19]. Fabbro [11] has explained, via the weld cap appearance when stopped, how the arrangement of two or three (triangle) beams broaden and
govern the melt flow and the pool shape. The influence of multiple beams (e.g. as a matrix) or of shaped beams (e.g. C-shape, for battery welding) generated by DOE (diffractive optical elements) on the heat flow conditions during conduction mode laser welding was studied and optimized by heat flow FEA [20], supported by thermal imaging.

Another option for beam shaping is provided by scanner optics, where sufficiently fast beam movement (e.g. circles, ellipses, etc.) can enable quasi-steady state conditions. One strategy studied was to oscillate the laser beam across a filler wire, fed in leading position. This has led to the formation of stable buttonholes in the melt pool, observed by HSI. While the buttonhole mode led to even smoother weld cap surfaces than by the keyhole mode, in the transition regime between keyhole and buttonhole welding the buttonhole periodically detached into larger pinholes in the solidified joint [2]. These buttonholes do not appear as Catenoids but have steeper vertical walls with sharper transitions to the top along with a rounded horizontal shape. For the same case, the buttonhole occasionally formed even during CFD-simulation of the weld pool, including pinhole detachment under certain conditions [3,4].

When the authors carried out a wider study on the influence of multi-spot laser beam patterns on the melt pool during welding of duplex steel, from high speed imaging the formation of buttonholes was noticed, for most of the tailored blank cases. Since these aspects and their combinations were yet hardly studied by high speed imaging, selected results are presented and discussed in the following.

2. Methodology
Tailored blank laser welding was carried out for a butt joint configuration of a 1.8 mm thick steel sheet with a 1.1 mm thick sheet, as illustrated in figure 1(b), for zero gap. Six different multi-spot patterns were arranged according to figure 1(c) and the shown nomenclature. Apart from the different beam spots the experiments had identical parameters. It is worthwhile to mention that these six experiments were part of a wider study of 28 experiments, while all other 22 multi-spot welding experiments were carried out for butt joints of equal thickness, like in figure 1(a) (though also for 1.8 mm thickness), which can serve as reference. These experiments were part of a larger study of steel welding for electric vehicles, particularly based on squared steel tubes as frames. In the project, laser beam welding was compared to electric arc welding. The sheets had a length of 100 mm and a width of 70 mm. The edges were mechanically cut. Duplex steel was applied, grade DP800 for the 1.8 mm thick sheet and the stronger grade DP1000 for the thinner 1.1 mm sheet.

![Figure 1. Butt joint configuration: (a) cross section for equal sheet thickness, (b) step joint (tailored blank, here presented results), (c) top view of arrangement of the different multi-spot cases.](image)

As already illustrated in figure 1(c), six different multi-spot arrangement of a fibre laser beam were applied and compared. The multiple spots were formed through a special optics, named *quattroXX*, manufactured by the company *AdlOptica*, Germany. The optics is placed between the collimator and the focusing optics. The *quattroXX*-optics is based on beam splitters. By adjusting two rings that rotate the optical elements, it can be chosen to form one, two, three or four beam spots, which can be numerically simulated beforehand. In addition, within certain limits the distance between the spots, the power and the power density level per spot can be chosen. However, at least in one direction symmetry will be maintained. Another parameter is the arrangement of the beams relative to the travelling direction, i.e. rotation. Lateral off-set would be a further option, not studied here. Corresponding to figure 1(c), the measured spots are shown in figure 2(b), and 3D-visualized in figure 2(a) for Case IV. Case II has a power of 1500 W per spot and an average power density of 1.7 MW/cm² (spot diameter 333 µm). Case III: outer spots 1120 W, centre 760 W; Case IV: 840 W and 660 W (= 0.76 MW/cm²).
The choice of the beams and arrangements is based on assumptions for the generation of thermal cycles with a second peak for tandem spot arrangements, an asymmetric melt pool, or distribution of the heat between the thicker and thinner sheet, among other hypotheses for cooperation between the beams.

From the wider experiments of butt joint welding of equal thickness these six spot arrangements have mainly led to the formation of separate keyholes per beam, only occasionally combining. The welds were stable. A buttonhole has never formed. So it was interesting to continue the study for welding two sheets of different thickness, because of the added complexity of asymmetric conditions.

Any other process parameters were kept unchanged for the six beam spot cases. The experimental set-up is shown in figure 2(c). A 5 kW high power Yb:fibre laser was used (IPG, YLS-5000-S2T-Y16, wavelength 1070 nm), operated at 3 kW, continuous wave. The process fibre had a core diameter of 200 μm (focal length 250 mm, collimator focal length 150 mm), generating 333 μm-spots (focal plane at the upper surface level of the thicker sheet, Rayleigh length ±6 mm). After the processing fibre, the beam parameter product was 6 mm·mrad. The initially random polarization of the laser beam is expected to be partially altered towards linear polarization, by each of the four beam splitters of the quattroXX optics. This requires further investigation. The polarization can affect the Fresnel-absorption behaviour at the boiling front. The optics was mounted to an industrial 6-axis robot (ABB, IRB 4400 M98A). The laser beams were moving at a speed of 3 m/min while the clamped workpiece sheets were at rest. Argon was applied as shielding gas from the top (flow rate: 18 L/min), while the root was not shielded.

Two high speed cameras were employed, according to the set-up in figure 2(c), to simultaneously observe the melt pool top surface. Camera Cam1 (RedLake NR4-S2) observed the process from a more vertical position (lateral inclination to the sheets 65°), at 4000 fps, Cam2 (Photron Fastcam mini UX100) more from the side (lateral inclination 45°), at 25 000 fps. Cam1 was mounted at the robot arm to follow the whole process (~2 seconds), which added some oscillations to the recording. In contrast, Cam2 was employed in a stationary manner, which avoided shaking but enabled only recording of a half the process (~1 s). An illumination laser beam (diode laser, Cavitar, beam power 100 W, wavelength 808 nm) was applied for sufficient brightness while simultaneously blocking the processing laser light and most of the process emissions by a narrow band filter around the illumination laser wavelength. The resulting high speed images were studied and analysed with the respective camera software as well as with Fiji/ImageJ software.

3. Results and discussion
A survey of the main observed behaviour of the weld pool for the six beam cases is shown in figure 3. Different operating modes as a function of time during welding can be distinguished. The first period of recording (white bar in figure 3, about 200 ms), when the laser beam is switched on, followed by ramping up the welding speed, starts always with a clear beam-print through the simultaneous initiation of keyholes. Once the constant speed was reached, all processes still required a certain run-in time (black bar in figure 3, lasting 50-500 ms, depending on the beam case) until a stable mode of operation was
achieved. Although showing interesting transient melt flow phenomena, these two initial periods will not be discussed below, similarly the final beam switch-off period (second white bar). The yellow bars correspond to the main stable modes of operations achieved, which will be presented and discussed in the following. While Case IV.T developed a typical stable melt pool for laser welding, although with four keyholes, for the other five cases a large stable buttonhole (BH) has formed. For three cases, II.T, III.T and IV.L, a certain change in the conditions has led to switching to a different stable mode (blue bar), which is also interesting to compare, although not deliberately planned, and will be discussed below. Otherwise all modes remained stable until either a change in conditions took place or the laser beam was turned off. Since metal melts usually react in the order of 10 ms to fluidmechanic changes, all operational modes that lasted longer than 100 ms in a similar behaviour and scale were regarded as stable. For some of the run-in periods it was a question of definition whether to already include part of their period into the stable mode, particularly for Case IV.T.

Cases:

| Cases | Description |
|-------|-------------|
| II.L  | 2 KH, trans. 2 boiling fronts: leading and left rear; large crater; bottom BH varies in size and disappears |
| II.T  | 2 keyholes, transients Stable 2-front-step-BH, short pool Oxides: KH, melt split BH |
| III.L | BH, jet variations Stable: 2 keyholes plus boiling front with BH, short pool |
| III.T | 2 boiling fronts, 2 stable melt jets, combining behind Central KH, 2 jets 2 jets keep split, wavy perforation |
| IV.L  | BH variations Stable BH, short pool BH shrinks Beam defocusing; no KH, no BH |
| IV.T  | Stable, right beam tries BH Four stable keyholes, no BH, stable pool |

Figure 3. Operating modes of the melt pool as a function of time for the six laser beam cases; white: switch-on/-off periods; black: transient run-in phases; yellow: stable operating modes; blue: different modes through parameter disturbances. (KH: keyhole, BH: buttonhole).

Figure 4 shows typical weld cross sections. For Case IV.T, the common weld pool without buttonhole, a suitable transmission from the thicker to the thinner sheet was achieved, despite some vertical edge mismatch. The usual narrowing of a weld towards the root can be seen. For Case II.T, as one example of welding with a stable buttonhole, the cap became much narrower (top: 45%) and the root is 40% wider than the cap, which will be discussed below. Undercuts have formed for this case. Narrowing of the weld cap can be desirable and hence one motivation for welding with a buttonhole.

Figure 4. Typical cross section of a welded joint for a case with buttonhole, here II.T, where a more narrow weld seam was generated, while wider for the regular weld pool for Case IV.T. Weld surface appearance (cap and root): Case IV.T: no BH, regular weld, wider. Case II.T: stable weld via buttonhole, fails later (cut). Case III.T: stable weld via buttonhole, fails later (wavy perforation).
Figure 4 also displays examples of resulting weld surface appearances. All welds had a stable appearance throughout, except the final phases of the three cases mentioned where the conditions have changed. For Case II.T it can be seen that the stable weld suddenly changes to a perforated, interrupted track. The mode change was triggered by a short pollution disturbance at the surface. In a short final period the process changed back to a stable buttonhole, hence a stable weld appearance again. For Case III.T the stable weld changed to wavy periodic interruptions and holes. From HSI it became obvious that the boiling fronts became weaker and finally disappeared, which indicates that the beam focus drifted away, or the laser power decayed. Note that the left hand regular weld surface appearances for Cases II.T and III.T are representative for all welds. Case IV.T shows a stable weld when no buttonhole was formed. This weld cap became wider. In most cases the root showed a slight reinforcement, while exceptionally a slight undercut or underfill has formed.

In the following, based on representative high speed images, the six beam cases will be presented, discussed and compared. A scale can be provided horizontally but measurement is limited due to the 3D complex melt surfaces, including the inclined camera views. The 0.7 mm edge step also serves as scale.

Case II.L - Two beam spots, longitudinal (tandem)

First, high speed images for the tandem case II.L are presented in figure 5.

![Image](image_url)

**Figure 5.** Case II.L, TBLW with two laser beams, longitudinal (tandem) beam arrangement; (a) high speed image of the melt pool, top camera view (Cam1), (b) side camera view (Cam2), showing a hole, (c) Cam 2, no hole; (d) streak image extracted from (a) (line); (e) sketch of the melt pool (1: leading boiling front at the thick sheet, 2: at the thin sheet, 3,4: corresponding fast, thin melt flow channels to left and right, 5,6: slowing down and recombining of the melt, 7: first new edge, 8: second new edge formed, 9: pool solidification); (f) left (thick sheet) melt flow field from first to second boiling front.

As illustrated, the leading beam generates a boiling front, both, on the thick and thin sheet, accelerating melt to the rear, via the sides and underneath. The trailing beam would not be needed. It experiences already an environment where the melt was moved to the side channels. However, the trailing beam generates a second boiling front, now against the travelling direction, which is unusual for
laser keyhole welding. It processes melt downwards and determines the rear shape of the large hole, followed by the bigger melt pool tail. This better control of the keyhole rear side can be an advantage, to calm down the melt pool, avoiding defects.

The appearance of holes through the crater melt is fluctuating (for the limited angle of the two cameras), see figures 5(b),(c). The kind of hole can be a large buttonhole, or either of the two beams drills a smaller hole at the crater bottom. In particular, the trailing boiling front accelerates material downwards, for redistribution. However, at the top, the rim of the big crater keeps in a very stable shape, which can be well seen in the streak image, figure 5(d) (the low frequency oscillations induced by the robot movement need to be subtracted/ignored). The trailing beam ensures to keep the boiling crater big and its rear wall stable. The intermittent formation of full penetration holes in this big crater can be seen in the streak image, too.

Case II.T - Two beam spots, tilted

Figure 6(a) shows a high speed image of a buttonhole forming, for Case II.T. As illustrated, also in a sketch, figure 6(c), the leading laser beam to the left generates a deep boiling front at the thicker sheet which also transmits to the thinner sheet. In absence of significant underfill and spatter, the wide hole is evidence of redirection of the melt to the sides. Since the melt film is very thin at the top, for balance of mass the melt has either to achieve very high speed or the film becomes wider at the bottom, or both.

![Figure 6](image)

**Figure 6.** Case II.T, two laser beams tilted; (a) HSI, Cam1; (b) HSI during start, emphasizing the two laser spots; (c) sketch of the left leading (1) and right trailing (2) boiling front.

The root width of the welded joints is slightly wider than the cap (see figure 4), indicating some channel widening, while simultaneously faster melt movement was observed. The significant length of the hole indicates that the melt has no urge to slow down. Probably due to high momentum, the two streams recombine far behind the boiling front. While the side wall appears steep and rather flat, far from a surface tension equalized Catenoid, refer to Eq. (1), the rear shape of the buttonhole tends more to the latter. Compared to the left beam just succeeding through the thicker sheet, the right, trailing laser beam has an excess of beam power for the thinner sheet. This easily enables a second boiling front that widens to a big hole, driving the melt to a channel to the right, while a significant portion of the laser beam can be expected to pass through the hole. The tilted arrangement permits a stable, wide buttonhole.

As indicated in figures 3 and 4, towards the end the laser beams were hitting some oxide flakes at the surface. Within milliseconds the mode of operation has changed, to a stable left keyhole, a right boiling front and splitting of the melt, causing a cut. After 20 mm, the stable buttonhole mode restarted.

Case III.L - Three beam spots, longitudinal

When three spots are arranged in longitudinal direction, along the edge, see figure 7, the first stronger spot and the second weaker spot generate keyholes, which occasionally combine. While those two beams and keyholes start creating a pool similar to single beam welding (though here asymmetric, TBLW), the third (again stronger) laser beam (Case III.L) generates a boiling front and a stable long buttonhole.

As HSI shows and as illustrated, a clear flat wall forms in the thicker sheet, similar to Case II.T, figure 6, but even more stable and pronounced. This corresponds again to a thin, fast melt film as a
channel, while the buttonhole closes with a more curved section into the wider pool. The streak image (a camera array recording plotted over time; here selected the horizontal yellow line in Fig. 7(b); for further explanation see [10]), selected across the two keyholes and the buttonhole, confirms that the buttonhole and its boundaries keep very stable (again disregarding the robot oscillations). The two keyholes seem to carry out a preparatory melt formation while the third beam, the open boiling front, easily sustains a big open hole while fuelling the two side channels with accelerated melt. Although the III.L-beams do not widen the boiling front, the third beam was sufficient for a very stable buttonhole.

Figure 7. Case III.L; (a) sketch of the boiling front (marked 3), accelerating the melt to a thin side wall (4), slowing down and widening behind (5) to a Catenoid-like surface; (b) HSI, Cam1, showing the two leading keyholes (KH1, KH2) the boiling front (3), the buttonhole (BH) and the pool (6); (c) streak image (array recording over time, see [10]) extracted from the yellow line location in (b).

Case III.T - Three beam spots, tilted

The melt behaved very differently when the three beams were tilted, Case III.T, see figure 8. The leading beam (1) on the thin sheet and the trailing beam (3) on the thick sheet generated two separate boiling fronts and melt jets, which only recombined at some distance behind to a common melt pool. The rear melt part resembles the (torus-like) Catenoid buttonhole curvature, while the two front melt parts are separated (disregarding the solid connection). Initially, figure 8(b), the weaker central beam (2) hardly generated boiling but at a later stage it formed a continuous keyhole, connecting to the leading boiling front (1), figures 8(a),(c), but not to the trailing one (3). At the final stage of the run, the two parts became only periodically welded together, followed by regular wavy gaps, see figure 4. Basically such concept of separately controlled melt jets, which combine behind, can have interesting advantages and applications. Here it was apparently vulnerable to some changing conditions (e.g. lateral distortion of the sheets, resulting from heat accumulation during the welding) that kept the jets separated, see figure 8(d). Note that the left jet was rather thin and did not fully penetrate the thick sheet, which however was succeeded behind, when combining with the other jet.

Figure 8. Case III.T, three beams, tilted, HSI; (a) Cam1 and (b) Cam2, two boiling fronts (1,3) and melt jets, forming a buttonhole-like geometry; (c) now also the weaker central beam spot (2) generates a keyhole; (d) later the jets remain separated, causing an intermitting gap instead of a weld seam.
Case IV.L - Four beam spots, longitudinal

According to figures 1,2, four spots were arranged as square, with almost equal power, here in-line with the travelling direction, Case IV.L. High speed images of the weld pool in figure 9 show a stable buttonhole that is quite similar to the Cases II.T and III.L. The beams share the boiling fronts that they develop, as illustrated in figure 9(c). At the left hand side, the leading beam carries out the main melting of the thick sheet into depth, while the trailing beam contributes to a smaller extent, probably accompanied by significant beam transmission through the buttonhole. The melt flows also down to the right hand side where the leading right beam again performs most of the melting, though now at the thinner sheet. There again some excess beam power can transmit through and the buttonhole is easily kept open, a mechanism similar to Case II.T. The boiling front generated by the trailing beam at the thin sheet can hardly be distinguished from the leading beam and again most likely contributes to a smaller extent to the melting and melt acceleration, while part of the beam is transmitted. The four beams ensured a stable large buttonhole, probably with much excess of power. As indicated in figure 3, after a while the buttonhole was shrinking in length but remained stable. Towards the final stage, it seemed as if the beams became weaker, either by some fading of the focal plane position or by a power decay, in an undeliberate but interesting manner. One reason could be heating or pollution of an optical element. Finally, probably because the spot power densities dropped below the boiling threshold, all four keyholes and the buttonhole disappeared and conduction mode welding took place.

![Figure 9. Square of four beams, in-line, Case IV.L; (a),(b) HSI of the weld pool for Cam1 and Cam2, respectively; (c) sketch of the melt pool.](image)

Case IV.T - Four beam spots, tilted

Finally, images of the melt pool for four beams, a square 45° rotated, are shown in figure 10. Notably, this is the only of the six beam cases studied here that did not form a buttonhole. The four beam spots clearly generated four keyholes, although occasionally two of them combined, accompanied by a stable melt pool, appearing to what is common for single spot laser keyhole welding. The weld became much wider than for all the buttonhole welds, and narrowed to the bottom, see figure 4.

![Figure 10. Case IV.T; four keyholes and a common weld pool, no buttonhole; (a) Cam2, (b) Cam1.](image)
During the first 500 ms (figure 3), it was well observed that the right beam attempts (enlarged, penetrating) to form a buttonhole, as highlighted in figure 10. While the other three beams partially use their energy for the thicker sheet, this beam has excess power for the thinner sheet, though apparently not enough in common with the other beams to form a buttonhole. The more beams are generated, the less power per sub-beam, for same total power. Later the conditions have stabilized such that these attempts stopped throughout.

4. Concluding remarks

- For multi-spot laser beam patterns, except for Case IV.T, a stable buttonhole always formed for tailored blank laser welding, probably because of the asymmetric conditions, while a buttonhole was never observed for the symmetry by same thickness plates.
- The appearance of the buttonholes differs from earlier Catenoid-like shapes, which can be caused by the here observed fast melt jets and correspondingly different fluidmechanic melt pool conditions.
- Multi-spot patterns can generate buttonholes with variants of open boiling fronts, instead of keyholes.
- The length of the buttonhole can vary; disturbances, like oxide flakes at the surface, can switch a stable buttonhole into a different stable melt shape-mode, even keeping two melt streams separated.
- Although the multiple beams and the generated buttonhole cannot yet be assessed through pros and cons, the concept offers different mechanisms for welding, particularly for the asymmetric complexity of tailored blanks with different thickness; some results indicate possible advantages.

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