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Encountering humping-driven defects using dynamic beam lasers

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Abstract

A crucial barrier in the assimilation of high-speed laser welding is the known humping phenomenon. In a generalized description, humping occurs at high feeding rates and involves unstable melt-pool velocity that competes with the resolidification rate, resulting in progressive accumulation and solidification of melt droplets along the weld seam. Moreover, humping can intensify other types of welding defects such as keyhole-porosity and cracks, and therefore, a combined resolution is needed to overcome these joint issues. Current experimental work in the elimination of humping and humping-driven defects displays partial success, in part, due to the current laser welding technology, which has a limited set of controllable welding parameters. Here, we demonstrate how different dynamic beam shapes can target humping-driven defects and how a sequencing approach in which different dynamic beam shapes are alternated in a fast sequence can temper the humping buildup and lead to minimization and elimination of several humping-driven defects at once.

Keywords: laser-welding; humping-defect; beam-shaping; shapes-sequencing

1. Introduction

Welding metals is a widespread requirement in many manufacturing industries such as electric vehicles, automotive, shipping and aerospace. The growing demand for fast, efficient, and high-quality welds is clear as the welds should be strong, reliable, and suitable to modern productions in the context of time frames. Laser welding is an appropriate solution, however, sometimes defects as humping, cracks and pores might appear in the welds. Some current solutions involve oscillation of the laser,(Kang et al., 2021; Li et al., 2020) power modulation,(Heider et al., 2015) and more. Nevertheless, while advancing to high velocity welding, the humping defect is still present.

Humps are small drop-like shapes appear on the top of the welds. They harm the smoothness and the appearance of welds, and they usually accompanied with other defects which weaken the products. Humping phenomenon is driven by an unstable melt-pool velocity that competes with the resolidification rate, resulting in progressive accumulation and solidification of melt droplets along the weld seam. As the laser light illuminates the material, it absorbs the energy and evaporation starts. Humps form when an absorption front inclination angle is low due to high welding velocities. The vaporization causes high pressure which induces the drag of molten material. The expanded vapor, which is directed normal to the front, drags some molten material upwards, while the recoil pressure, that also acts normal to the absorption front, causes material to flow laterally to the sides of the keyhole. These leads to heat accumulation at the top of the weld. Meanwhile, the high melt velocity and the surface tension cause a downward flow. Both melt material and liquid stream are directed up due to high momentum. Moreover, with the liquid stream, the heat also moves up which accelerates solidification at the lower part of the weld. The solidified material decreases the velocity of the molten material. The solidification starts from the sides towards inside the weld, and from beneath upwards, creating solid bridges at the keyhole. In addition, there is also an accumulation of molten material at the back of the melt pool. All these complex dynamics results with humps at high velocity welding.(Otto and Vázquez, 2018)

Although humping has been studied for many years,(Otto and Vázquez, 2018) there is no satisfactory answer for eliminating this problem. Current solutions involve adjusting the parameters of the experiments for minimizing humping by decreasing welding velocity,(Fabbro, 2010) welding power,(Ai et al., 2018) adjusting laser beam diameter,(Fotovvati et al., 2018; Otto and Vázquez, 2018) utilizing a dual beam so the second beam suppresses the

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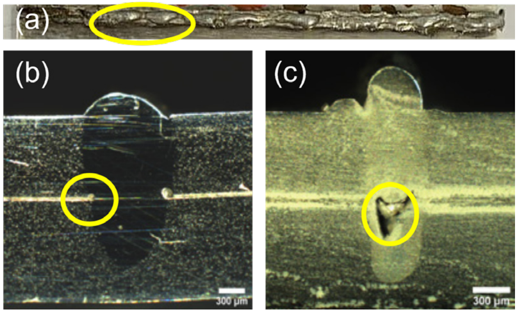

Fig. 1. Micrographs showing that high velocity welding gives rise to some common defects as: (a) humping (b) interface cracking of the overlapped plates and (c) pores.

hump formed by the first beam(Xie, 2002) and even other solutions such as applying an external magnetic field(Kern et al., 2000) are suggested. Here, we present a solution for minimizing humping defect while maintaining high welding velocity and power. We show that utilizing Civan's laser with its unique dynamic beam capabilities enables stabilizing the welding process by controlling power distribution and reduce keyhole instability through beam shape adjustment. The beam shaping and the sequencing of beams, every one of them expand the variety of parameters which affect humping.

2. Experimental

For the welding experiments, two plates of Al 5052 with total depth of 1.8 mm in an overlap layout were used. Aluminum 5052 has many uses in advanced industries due its high mechanical properties, corrosion resistance etc., however, laser welding of al5052 is complex due to keyhole stability issues and its tendency for hot-cracking , The utilized laser was a Single Mode Continuous Wave Civan's laser with the ability to create arbitrary beam shapes, beam steering at speeds of MHz and sequence of beams. The Dynamic Beam is derived from utilizing the Coherent Beam Combining (CBC) technology as well as the Optical Phase Array (OPA) technology. This combination allows to dynamically tailor beam parameters to the required application.

3. Results

High-velocity welding, at 500 mm/s, was implemented and showed that this high speed gives rise to many defects as humping (Fig. 1a), cracking (Fig. 1b), and pores (Fig. 1c). Utilizing beam shaping solves the cracks defects, as they are caused by a temperature gradient, and the beam shape provides proper temperature distribution. Among other defects, humping is the most problematic without a proper solution. Minimizing humping cannot be done at these high velocities by simple adjustments of laser power, focus, and spot size. At 250 mm/s, the welding process is stable while welding with a beam shaped like an hourglass producing a defect-free weld seam. Humping does not occur, and the weld quality in terms of pores, undercuts, and overfill seems excellent (Fig. 2a). this is provided by adjusting the beam shape to an hourglass, which expands and stirs the meltpool such that keyhole colapsse is inhibited and the temperature distribution at the center and periphery of the beam results in an improved weld quality.. However, at higher speeds of 500 mm/s, humping occurs, and the process welding is unstable, which translates to poor quality results with many defects (Fig. 2b).

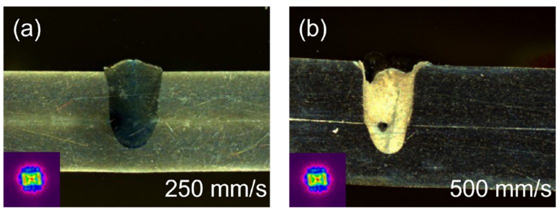

Fig. 2. (a) A micrograph of a cross section showing a defect-free weld which was produced at moderate velocities of 250 mm/s with a shaped beam of an hourglass. (b) A micrograph of a cross section showing a weld with defects which was produced at high velocities of 500 mm/s with a shaped beam of an hourglass.

while beam shaping can help improve weld quality, sequencing of shapes provides additional solution especially for high velocity welding where the overall stability of the welding process is more pronounced. Civan's lasers incorporate a novel sequencing approach in which several beam shapes are composed in series and used in a single weld move. Since the system is electro-optics based, it controls the switch between beam shapes extremely fast, meaning the sequencing of beam shape takes ~10 µs (illustrated in Fig. 3a). The concept behind this sequencing was to interrupt the high velocity buildup at the early stages of the humping phenomenon through different flow dynamics induced by different beam shapes. In the presented case, the chosen beam shapes were hourglass that stirs the melt pool and deprive porosity and a double-spot shape that concentrates intensity at the

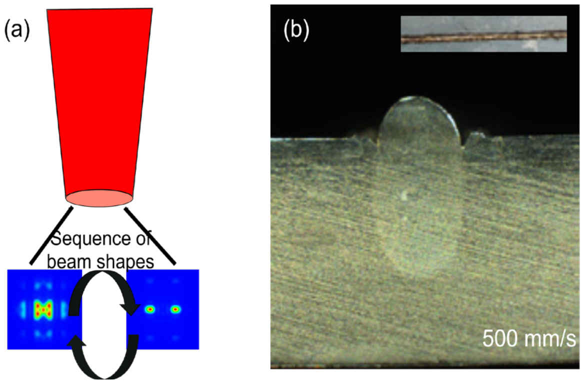

Fig. 3. At high velocities, a sequence of beam shapes prevents humping. (a) An illustration emphasizing switching between two shapes: hourglass and double-spot. (b) Microscopic photographs showing a top view (inset) and a cross section of humping-free weld at high velocity of 500 mm/s.

sides of the weld. These shapes were sequenced and resulted in elimination of the humping defect with minimal undercuts and no interfacial cracks and porosity (Fig. 3b).

While applying a sequence of shapes, a new set of parameters arise and can be altered. First, the frequency of the shape that influences the stirring within the melt pool, and second, the duration time of each shape which determines how long each shape would be activated. Both parameters can be defined for each shape. These additional degrees of freedom grant extra flexibility for producing defect-free welds. This is demonstrated in Fig. 4 which presents top view micrographs of two welds that show the influence of changing the frequency of beam shapes from optimal parameters (Fig. 4a, 500 kHz for both shapes) to non-optimal parameters (Fig. 4b, f1 = 300 kHz and f2 = 150 kHz).

A qualitative assessment of the humping irregularities was conducted using pixel intensity profiling using the ImageJ plugin (Fig. 4c). This examination aims to correlate the humping periodicity and the volume of the humps using changes in the pixel intensity along the weld seam. This allows a pseudo-3D analysis and allows a qualitative comparison between different experiment trails. In the graph, Y- axis corresponds to the changes in pixel intensity in arbitrary units, while X-axis corresponds to the seam length in mm. The colors of the curves represent welding using optimal frequencies (purple) and non-optimal frequencies (orange).

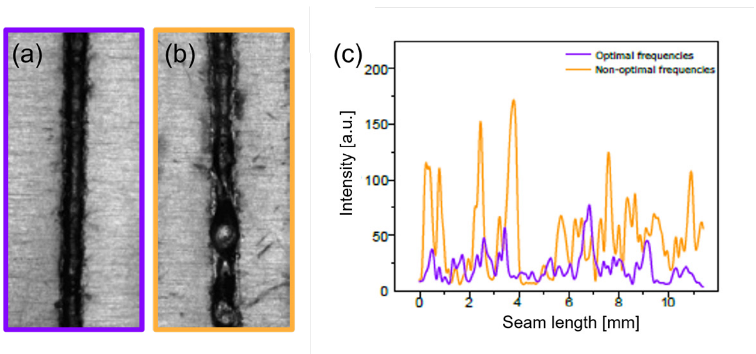

Fig. 4. Altering shape frequency in a sequence influences the weld seam. Top view micrographs of welds produced with (a) optimal (f = 500 kHz for both shapes) and (b) non-optimal (f1 = 300 kHz and f2 = 150 kHz) frequencies are presented. (c) A pixel intensity profiling which aims to correlate the humping periodicity and the volume of the humps. Y- axis corresponds to the changes in pixel intensity, while X-axis corresponds to the seam length. Purple curve represents welding using optimal frequencies and orange curve represents welding using non-optimal frequencies.

4. Conclusion

In this paper, the results demonstrate that minimizing the humping effect while maintaining high velocities can be achieved by sequencing of beam shapes. The sequence of shapes interferes with the melt pool flow dynamics buildup results in humping prevention. In addition, applying sequence adds extra freedom degrees as shape frequency and duration, that increases the process flexibility. Civan's laser with its unique qualities as designing any arbitrary beam shape and applying sequence of beams is an excellent solution for achieving fast, high quality and humping-free welding. Civan's Single Mode laser and its Dynamic Beam has a good control over the melt pool and the energy distribution. Both enable utilizing high powers and high speeds while minimizing many defects in particularly the humping defect and obtaining good results.

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