Optics and Lasers in Engineering 101 (2018) 89–98

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng

Factors affecting weld root morphology in laser keyhole welding

Jan Frostevarg

Luleå University of Technology, Div. of Product and Production Development Luleå SE - 971 87, Sweden

ARTICLE INFO

Keywords:
Laser welding
Hybrid welding
Weld root
Humping
Weld quality

ABSTRACT

Welding production efficiency is usually optimised if full penetration can be achieved in a single pass. Techniques such as electron and laser beam welding offer deep high speed keyhole welding, especially since multi-kilowatt lasers became available. However, there are limitations for these techniques when considering weld imperfections such as weld cap undercuts, interior porosity or humps at the root. The thickness of sheets during full penetration welding is practically limited by these root humps. The mechanisms behind root morphology formation are not yet satisfactory understood. In this paper root humping is studied by reviewing previous studies and findings and also by sample examination and process observation by high speed imaging. Different process regimes governing root quality are presented, categorized and explained. Even though this study mainly covers laser beam and laser arc hybrid welding, the presented findings can generally be applied full penetration welding in medium to thick sheets, especially the discussion of surface tension effects. As a final result of this analysis, a map of methods to optimise weld root topology is presented.

© 2017 Elsevier Ltd. All rights reserved.

1. Introduction

Welding is used in a wide range of industries for joining metallic components [1–3]. For production purposes, single pass welding is often desired, which can be accomplished for thin sheets by a variety of methods without concerns about root quality. For thicker sheets, high power Electron Beam Welding (EBW), Laser Beam Welding (LBW) and Laser-Arc Hybrid Welding (LAHW) [4–9] can be applied, offering deep penetration depths at high welding speeds in a single pass. These techniques offer lower heat inputs and faster cooling rates than traditional arc welding, which often requires multiple pass welding [1,3,10].

1.1. Weld humps

Deep penetration welding processes can give rise to quality problems [11], such as the imperfections illustrated in Fig. 1(a), including; undercut [12], inhomogeneous material mixing [13] (which can depend on process orientation [14,15] and the presence of a gap [13]), porosity [6,16,17] and centreline cracking [18]. For single pass full penetration in sheets thicker than 10–12 mm [19], LAHW is often associated with excessive root penetration, with corresponding limitations stated in the Standard ISO 12932:2013 [20]. This imperfection can be divided into continuous root sagging or the intermittent [21] formation of droplets, known as root humping [6,22,23] as shown in Fig. 1(b) and (c). This particular imperfection has also been called dropping [24], dropout [25], drop through [26], burn through hump formation [27] or chain of pearls [28], but root humping is the most common term. Excessive root penetration is associated with weld cap underfill [6] (material flows to the root) and root humping is also linked to porosity [24,29] and lack of fusion [21] which reduce the fatigue life of the welded component [30,31]. Root sagging on the other hand, is scarcely mentioned in the literature, and is considered a less severe problem.

Melt humping at the root is believed to have similarities to weld bead humping on the weld cap, which is normally associated with high welding speeds. Based on the conservation of mass, Berger et al. [32] investigated humping for both wide/shallow and narrow/deep welds. They observed that a thin melt pool that moves at high speed is sensitive to rapid solidification, potentially choking the melt flow and consequently initiating swelling of the melt. As the heat source moves away from the growing hump, the melt pool extends and can again get choked by melt pool solidification, creating a new swelling closer to the heat source. It was also observed that humps tend to form when the melt stream velocity far exceeds the welding speed. Surface tension is also important and increased oxygen content and melt speeds drastically increase the tendency for humping. Although hump formation at the root has similarities with hump formation on the weld cap, internal weld melt flows and gravitational forces have a large effect on root humping.

Blecher et al. [29] have surveyed occurrences of root humping for LBW and found that in almost all cases the process was due to having too high a heat input. Though not included in the survey, it was predicted that if LAHW was used the additional heat source could increase the chances of root humping.

E-mail address: jan.frostevarg@ltu.se

https://doi.org/10.1016/j.optlaseng.2017.10.005
Received 26 May 2017; Received in revised form 19 September 2017; Accepted 9 October 2017
0143-8166/© 2017 Elsevier Ltd. All rights reserved.

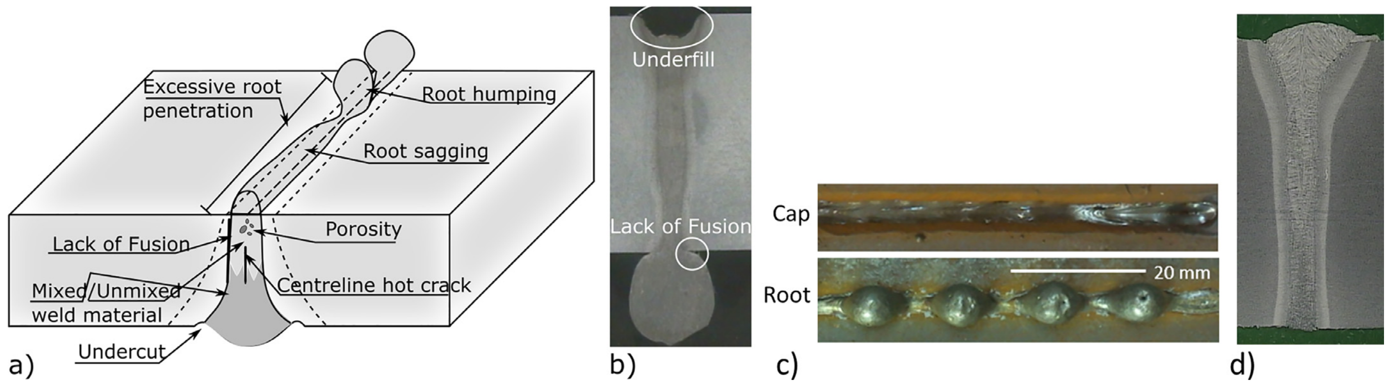

Fig. 1. LAHW (a) upside down illustration showing root imperfections. (b) cross section and (c) weld cap and root appearance [25]. (d) shows good root quality.

1.2. Observations of root humping

Studies of root humping have been made using High Speed Imaging (HSI) [33] and X-ray technologies. For LBW, Ilar et al. [21] studied the formation of root humps and found no correlation between hump size and distance, indicating instabilities in supply of melt flow to the root, which can be explained by keyhole instabilities. They also studied the flow dynamics of the weld cap and root simultaneously [23]. It was found that the top structure does not correlate with the appearance of the root and that the melt pool is wider at the top than at the root. Hump formation was found to be initiated at the end of the long melt pool tail, similar to the formation of humps on the weld cap. These findings are explained in more detail by Powell et al. [34].

Process windows for root humping have been found for LBW by Haug et al. [35] and for LAHW by Petring et al. [26] and Pan et al. [22]. For both processes, there are power input regimes categorized in order of increasing power as: (1). Insufficient Penetration (IP), (2). Root Humping (RH), (3). Good Result (GR) and (4). Over Penetration (OP), with root humping, occasional spatter and open pores at the root (a.k.a. root concavity or Shrinkage groove [20]).

Haug et al. [35] studied hump formation and process stability in the RH regime using a 1 µm laser on 12 mm steel. They found that the humps form when full penetration is not achieved directly by the laser but by conductive heating just behind the keyhole, and melt flows out to form the droplets. Additionally, the penetration depth of the keyhole was found to vary. Weld stability and intermittent penetration by 1 µm lasers has also been studied by others, e.g. using HSI [36]. Ohnishi et al. [27] looked at LBW with hot and cold wire with different shielding gas setups. They found that if the shielding gas is too effective, the oxygen content in the melt is reduced which leads to lower viscosity and less penetration, causing humps in the same manner as observed by Haug et al. [35] when the power input is too low for full penetration. They also observed the same trend for the power input from the wire in the process. Root humping occurred with cold wire and was reduced when welding with hot wire (due to the higher heat input).

The front of the keyhole has been observed by Eriksson et al. [37] who found that the flow down the keyhole front is wave driven for 1 µm (fibre laser) laser radiation. Absorption based models depending on laser wavelength were later made by Kaplan [38,39]. Locally, the waves absorb most light on the wave shoulders for 1 µm light, and in areas where the keyhole wall is very steep for 10 µm light (CO_2 laser), which tends to create a smoother melt surface on the keyhole wall in the case of CO_2 laser welding [38]. It has also been shown by simulation that the keyhole stability is higher when using 10 µm lasers [40]. Globally, the front is wavier for 1 µm and the melt gets more thrust downwards. When using 1 µm lasers at high enough power densities, the welding process can fail and transform into a process called vapour pressure fusion cutting [41].

Haug et al. [35] also studied the influence of laser wavelength, (1 µm and 10 µm) on deep penetration welding. They found that process behaviour differs, as does the resulting robustness and seam quality. The 1 µm wavelength laser has a narrower process window in terms of power output and weld speed, but the 10 µm wavelength laser generates more spatter.

Pan et al. [22] used X-ray photography with tracers of tungsten for one case when welding with and one case without hump formation. When having root hump formation, two time-series are shown. In the first, the hump forms through an opening which is not directly beneath the keyhole, as also described by Haug et al. [35]. In the second time series, the tracer exits the keyhole at the rear and is moved by a flow along the root, below the sheet bottom edge, to the already formed hump, matching the observations of Ilar et al. [21]. When there are no hump formation, the tracer follows a flow just above the sheet bottom edge and later moves back to the rear of the keyhole in a backwards current.

HSI was also made by the present author, observing root humping [25]. As shown in Fig. 2, melt is shown to be pushed out near the keyhole and then flows beneath the sheet bottom edge. It was shown that surface tension can keep large volume droplets from escaping the melt and that a new hump will start to form close to the process exit after the melt flow to the previous one has solidified.

1.3. Process theory

Besides these experimental observations, there are also theoretical models which examine the pressure in the keyhole. These models assume that the melt above the opening at the root needs to be contained by surface tension, otherwise melt will escape. Petring et al. [26] developed a 2D pressure balance equation for maximum root width at any location along the root length, which takes into account the downwards momentum of the melt. Blecher et al. [29] uses a force balance equation and assumes a circular keyhole exit with surface tension acting as an upward force that prevents the melt from exiting. A static gravitational force from the mass of the melt pool acts downwards. Frostevarg et al. [25] reasons that surface tension is responsible for redirecting the downward flow, that would otherwise be ejected as spatter. Depending on the width of the process zone exit, the surface tension becomes weaker for wider diameters. Bachmann et al. [42] successfully applied electromagnetic backing to suppress root humping in stainless steel and aluminium [43], this technique was also used for duplex steel by Avilov et al. [44]. An inductive contactless electromagnetic force is applied to counter the hydrostatic pressure at the root, preventing the melt from exiting the process zone. The force needed is based on a 2D static pressure model, considering contact angles for a spherical exit. The forces included are gravity on the mass above the exit, surface tension, the Laplace pressure and electromagnetic pressure. For partial penetration, it is shown in a 3D simulation model of LBW by Pang et al. [45], that the solidified fusion zone (FZ) will be both deeper and wider than the

Download English Version:

https://daneshyari.com/en/article/7132001

Download Persian Version:

https://daneshyari.com/article/7132001

Daneshyari.com