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The stability of laser welding with an off-axis wire feed

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ABSTRACT

The concept using an off-axis filler wire during laser welding is introduced here in order to provide added process robustness considering gap width variations. Its stability is investigated with respect to gap width, welding speeds and powers. Geometry of the welds is analysed by tracing of weld cap edges and joint cross sections, connecting trends to weld parameters. High speed imaging and streak images are used to further study and describe sequences of events, including undercut formation. Formation of imperfections are found to be mainly correlated to wire feed position variations at the surface due to irregular melting of the wire tip.

1. Introduction

Joining processes are essential in the field ofmanufacturing. Among the available choices, laser beam welding (LBW) is a fast process that also is considered to be easily automated. It has high energy density and precision, producing narrow heat effected zones. A drawback of autogenous LBW is the tight tolerances for joint edges. Lampa et al. (1995) studied the effect of gap width on the laser welding process. They showed that when the gap reaches a critical size, about 10% of the material thickness, the melt available is unable to bridge it. Fig. 1a and b illustrate the cross sections achieved by autogenous laser welding with increasing gap width.

Addition of filler materials reduces the need for high joint tolerances and therefore reduce costs. Applications of using filler wires during LBW for thin steel sheets has been mentioned since the early 80 s, as well as for thick plate multi-pass welding up to 50 mm by Arata et al. (1986). Kong et al. (2013) demonstrated laser welding of 6.63 mm thick hot crack sensitive high strength steel with a single pass. The heat affected zone in laser welding with cold wire was shown to be narrower compared to hybrid laser-gas metal arc welding. In hybrid laser-gas metal arc welding, there are 2 heat sources: laser and arc, whose characteristics and interaction produce more complex thermal cycles, as opposed to laser welding with cold wire. Sun and Kuo (1999) concluded that for a butt joint of 2 mm thick carbon and stainless steels, a 1 mm wide gap can be bridged, but the need for good filler wire control was emphasized. They also consider that wire is considered a good method to deposit material to the joint, having 100% deposition compared to e.g. blown powder where material losses occur. Fig. 1c illustrates the cross section of a weld with addition of a filler wire for the same gap width as in Fig. 1b.

Other examples of single pass LBW with cold filler wire for various materials and thicknesses include; single-pass 6–8 mm thick ship building steel by Huang et al. (2016) and 6.63 mm thick high strength steel by Kong et al. (2013). For multi-pass welding, examples are also extended to; 1.8 mm thick aluminium alloys in a T-joint by Tao et al. (2013), 20 mm thick austenitic stainless steel by Jokinen et al. (2003), 10–60 mm thick austenitic stainless steel by Karhu and Kujanpää (2015) and 16 mm thick AISI 304 L stainless steel in 2 G configuration by Sun et al. (2017) who also emphasize the need for good filler wire control.

Different types of seam tracking or gap width measurement methods for adaptive control of welding processes are possible. One such system is described by Huang and Kovacevic (2012), which uses a laser based machine vision system for weld joint monitoring. Xu et al. (2012) describe an optical vision sensor system for seam tracking during the gas tungsten arc welding process. Such a system can be used to adjust wire feed speed based on gap volume, optimally position the wire and beam during laser welding with cold filler wire.

Wire can be added in two directions: leading and trailing. Leading feed, i.e. feeding the wire into the leading edge of the keyhole is generally chosen. Zhao et al. (2016) found that the stability and melting efficiency of the wire in leading feed was higher than that of the trailing feed when the wire was inserted into the melt pool while welding mild steel. According to Syed and Li (2005), leading wire feed and smaller feeding angles produced lower surface roughness in cladding. Trailing feed, especially with low feeding angles is said to interact with the solidifying edge of the melt pool and forms a saw like appearance, called serrations.

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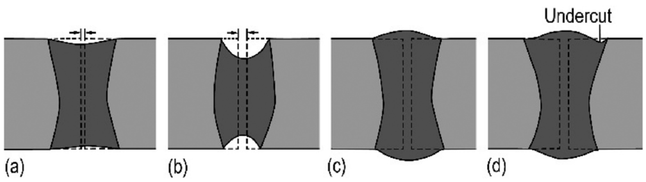

Fig. 1. Cross section of welds: (a), (b) without filler wire, where (b) has a larger gap prior to welding; (c), (d) welds with filler wire, where (d) weld has an undercut imperfection.

The filler wire in leading position obstructs the view of the seam necessary for adaptive control. An off-axis wire feed can be used to handle the requirements of the system and to increase process flexibility. However, use of this setup has hardly been applied due to the fear of unfavourable melt flows and weld seams.

Some imperfections are likely to form during welding, whose shape and size affect the mechanical properties of the joint. Undercuts are one such surface imperfection and can be described as an unwanted groove at the edges of the weld toe. Bell et al. (1989) found that the depth and root radius of undercuts affect stress concentration and thereby can reduce the fatigue strength of welded joints. Undercuts are usually regarded as a severe imperfection and most welding standards have very low tolerance for them. Eriksson et al. (2011) concluded that at high welding powers and speeds, severe undercuts are formed as a result of the backward flow of melt and its solidification along the centreline with reduced contact to the sides. Berger et al. (2011) also described the dependence of humping formation on melt flow velocities, an imperfection occurring together with undercuts at elevated weld speeds. Frostevarg and Kaplan (2014) explained causes for different kinds of undercuts, but they always form at the weld bead-base material interface at the end of the process zone, before the actual melt pool behind the process. Underfill of a joint can be suppressed by adding more material to the joint, but undercuts can still form. An illustration of a weld cross section with undercuts can be found in Fig. 1(d).

High speed imaging (HSI) as a technique to observe laser processing has been used since the 80′s by Arata et al. (1985), and is seeing an increase in applications. The technique has been developed and increased quality of lenses and camera capabilities enables faster filming at higher qualities so more detailed events can be observed. Applying bandwidth filter in front of the lens and using matching illumination laser enables observation through the processing light, revealing process mechanics and melt flows, Fig. 2a. One method of analysing the videos is streak imaging, where a single pixel wide line is taken from a video, at the same position of every frame, stacked against one another Fig. 2b and c. The resulting image describes the transformation of an event through the length of the video in a single figure. The technique was used by Eriksson (2010) to study fluid flow in laser welding and Frostevarg et al. (2014) to compare arc mode and undercut formations in laser-arc hybrid welding.

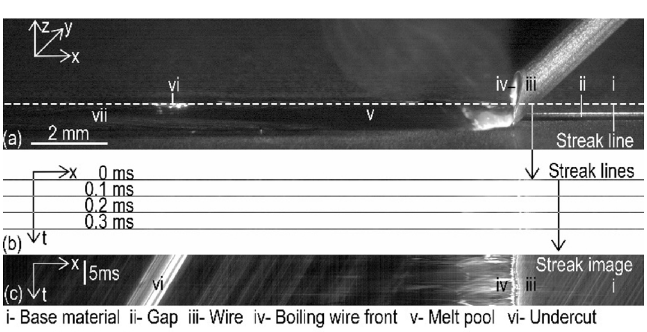

Fig. 2. (a) Frame from high speed video, inclined 30°, (b) stacked streak lines (streak line vs. time), and (c) resulting streak image.

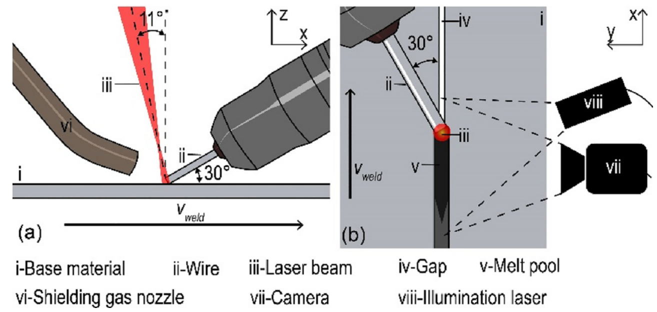

Fig. 3. Experimental setup (a) side view, and (b) top view.

In this paper, stability of LBW of with an off-axis wire feed in leading direction (allowing seam tracking close to the process) is investigated. Morphology of the welds and events forming irregularities are analysed using surface images, HSI and streak images.

2. Methodology

2 mm thick austenitic stainless steel sheets (304 L) were welded together in a close-to-zero-gap butt joint configuration, with added filler wire (1 mm in diameter) to bridge the gap and ensure good mechanical properties. The LBW process had an off-axis wire feed in leading direction, Fig. 3. The chemical composition of both the base material and filler wire are presented in Table 1.

2.1. Equipment and experimental procedure

In all experiments, the setup shown in Fig. 3 remained the same. An IPG fibre laser with maximum power 15 kW, wavelength 1070 ± 5 nm, 400 µm output fibre diameter and beam parameter product 14.6 mm.mrad was used in continuous wave (CW) mode. The optics used was Precitec YW50, with 150 mm collimator lens and a 250 mm focussing lens creating to create a focal spot diameter of 0.67 mm. The focus was positioned 8 mm above the surface of the plates, producing a theoretical Gaussian spot size 1 mm width at the surface, so that the laser beam irradiated the gap and the full width of the wire. The beam was inclined at 11° to the vertical axis to avoid back reflections. The welds were carried out using a 3-axis ISEL FlatCOM L150 CNC system with test plates clamped to a linear motion table. Edges of test plates were laser cut and the gap was varied between 0 and 0.3 mm. For each chosen gap width, two appropriately sized spacers were placed at each end between the test plates, and the plates were clamped tightly. It was verified that the gap width remained constant, with maximum variation of 10%, in the experiments by streak imaging.

An ESAB MEK 44C was used to feed wire in an off-axis leading direction. The wire feed was angled, 30° to the horizontal plane and 30° to the seam on the left side of the welding direction. The wire was positioned at a 0 mm distance from the base material, allowing it to glide along the gap.

The required wire feed to fill gap volumes having width l and thickness t, were calculated to have 15% reinforcement (resulting reinforcement factor, k = 1.15), as

$$v_{wire} = k \times \frac{4 \times v_{weld} \times l \times t}{\pi \times d^2}$$

where v_{wire} is the wire feed speed, v_{weld} is the welding speed and d is the wire diameter. In cases of having $l = 0$ mm gap welds, the wire feed was 1.5 m/min (minimum limitation of equipment).

The laser beam was positioned to irradiate both the base material and the wire. All welds were 180 mm long, shielded by argon supplied at 12 L/min to both the weld cap and root, where a tube provided shielding for the cap during processing and the fixture cavity of the root