Investigations on the Specifics of Laser Power Modulation in Laser Beam Welding of Round Bars

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Abstract
Welding round bars of large diameters in a rotational laser beam welding process corresponds with weld pool bulging and the risk of weld defects. Power modulation is a promising approach for bulge reduction and for keyhole stabilisation to achieve superior weld quality. The following investigations are about the specific effects of power modulation for round bars with a diameter of 30 mm. The welding speed is 0.95 m/min and argon is used as shielding and process gas. Triangle shaped power modulation at 8 kW average laser beam power, 0/2/4/6 kW amplitude power and 2/10/50 Hz modulation frequency is used for the round bar welding of a 1.4301 steel alloy. The welds are evaluated by visual inspection, metallographic cross sections and scanning acoustic microscopy. The amount of weld defects increases at medium and high power modulation, but weld pool bulging is already reduced at low power modulation. Weld pool bulging can be impeded by a low normalised power modulation frequency of 0.05 and a high modulation depth of 0.86. The power modulation’s advantages of weld mixing and degassing do not apply to rotational round bar welding because of the linear welding speed’s gradient from the specimen surface to the centre.

Keywords Laser beam welding · Power modulation · Weld pool bulging · Keyhole stability · Round bars · Steel alloy 1.4301

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Introduction

Welding of round bars with large diameters is usually done by friction welding, which is an unflexible process with the need of post processing [1]. In contrast, laser beam welding is a highly flexible process with low processing times and one laser setup can be used for several additional applications like surface treatment or cutting [2]. Prior to a successful application of laser beam welding for round bars, specific process development is necessary. In previous investigations [3] weld pool bulging was found, which can effect weld defects. Keyhole gas can remain in the weld [4] and solidification cracks can be effected since the bulge solidifies last [3, 5]. Power modulation is a promising approach for bulge reduction and keyhole stabilisation. It can be devided into spatial power modulation realised by beam oscillation and temporal power modulation realised by periodic power profiles [6].

Artinov et al. [7] and Bachmann et al. [8] investigated the formation mechanism of the bulging effect. Slight bulging begins at 6 mm weld depth and it is fully developed at 9 mm weld depth. It occurs, if the top and bottom melt circulations are separated by a necking region. The bottom melt circulations originate from a high recoil pressure at the weld bottom. Thus, the melt is pushed against the weld pool’s rear wall, where further material is melted, and a bulge forms. Nearly no intermixing occurs between top and bottom melt circulations.

Regardless of constant welding parameters, keyhole fluctuations with specific frequencies occur. Matsunawa et al. [9] identified frequencies of up to 40 Hz specific for their parameters in aluminium, mild and stainless steel welding by analysing the ejection of plasma from the keyhole. The authors reduced porosity by modulating the welding power in pulsed laser beam welding at a frequency of 100 Hz and different duty cycles.

Shimokusu et al. [10] investigated the keyhole behaviour in pulse-modulated laser beam welding with 13.5 kW peak power. Saturation times for keyhole growth, which are increasing with increasing peak power, were found. After reaching the saturation time for maximum penetration depth, the gas plume height above the keyhole fluctuates and the welding process is less stable.

Neto et al. [11–13] investigated different profiles of power modulation and different modulation frequencies. The authors concluded that the increasing weld depth at increasing power modulation results from the duration of welding power above the average welding power. At low modulation frequencies, pore formation in the bead root occurred. The reason may be a keyhole collapse due to a saturation of the keyhole growth. At higher modulation frequencies, smaller pore formation in the weld middle occurred. The authors concluded that the modulation frequency is closer to the keyhole self-fluctuation frequency and less keyhole growth saturation and collapse occurred. Furthermore, wider weld beads were obtained at low frequencies and deeper weld beads at high frequencies. Using step-shaped power modulation, residual stresses and the susceptibility to cracks can be reduced.

Heider et al. [6, 14] used power modulation in laser beam welding of copper sheets with weld depths of up to 10 mm. The authors identified a normalised
modulation frequency of 0.2, see (1), with a frequency of 200 Hz and modulation depths of 75% and 86%, see (2), for keyhole stabilisation and weld defect reduction at 4 m/min welding speed. At a modulation depth of 46%, no reduction of weld defects was achieved. By increasing the normalised frequency the number of weld defects also increased. If the welding power was dropped below the power limit for deep penetration welding, the formation of gas porosity could be effected by the keyhole collapse. Furthermore, the weld depth increased slightly at high frequency power modulation and up to 30% at low frequency power modulation. The modulation effect on weld defects was not significantly influenced by changes in welding speed and focal spot diameter.

The normalised frequency $\nu$ can be calculated according to (1)

$$\nu = \frac{f_M \cdot d_f}{v}$$

where $f_M$ is the modulation frequency, $d_f$ is the focal spot diameter, and $v$ is the welding speed [6]. Kroos et al. [15] found out already in 1993 that the keyhole’s oscillation frequency increases with a decreasing keyhole diameter and increasing welding speed.

The modulation depth $\Pi$ can be calculated according to (2)

$$\Pi = 1 - \frac{P_{\text{min}}}{P_{\text{max}}} = \frac{2 \cdot P_{\text{ampl}}}{P_{\text{average}} + P_{\text{ampl}}}$$

where $P_{\text{min}}$ and $P_{\text{max}}$ are the minimum and maximum welding power, $P_{\text{ampl}}$ is the amplitude power, and $P_{\text{average}}$ is the average power [6].

Kuo and Jeng [16] applied rectangular laser power modulation at 100 Hz modulation frequency and between 2.12 and 5.14 normalised frequency in welding of the stainless steel SUS 304 l and the nickel base alloy Inconel 690. By increasing the modulation depth up to 90%, porosity was massively reduced probably due to melt mixing and gas bubble floating. In addition, weld depth, tensile strength and fracture strain increased.

Besides porosity reduction, power modulation can also be used for crack reduction. Schäfer [17] investigated methods for hot crack reduction in laser beam welding of quenched and tempered steel. The number of hot cracks was massively reduced at 0.2 normalised modulation frequency, increased with increasing frequency and reduced with increasing modulation depth at welding speeds between 1 m/min and 6 m/min. The reason is a change of melt pool geometry from rectangular to tapered in the longitudinal section and the enhanced mixing of segregating alloying elements. According to [18, 19] there is no considerable difference in the effects of different modulation profiles like sinus or triangular.

In round bar welding, the linear welding speed decreases from the specimen surface to the centre and the energy per unit length increases in contrast to sheet welding [3]. Since power modulation in round bar welding is not state of the art the following two objectives will be investigated:
• Identification of power modulation specifics for round bars.
• Identification of modulation parameters for keyhole stabilisation.

The specimens are evaluated by metallographic cross sections to identify the weld shape and weld depth and by scanning acoustic microscopy to analyse weld defects in the whole weld volume. The stainless steel grade 1.4301, see Table 1, is used as specimen material.

Experimental Setup

A diode-pumped solid state disk laser system (TruDisk 16002, TRUMPF Laser- und Systemtechnik GmbH, Ditzingen, Germany) with specifications according to Table 2 is used for power modulated laser beam welding.

During welding the specimen is rotated and the laser processing head is held in one single position by a robot system (KR 60 HA, Kuka AG, Augsburg, Germany), see Fig. 1. The complete setup is described in detail in [21].

Table 1 Chemical composition of 1.4301 steel alloy in wt.-% [20]

| C    | Si   | Mn   | P    | S    | Cr   | Ni   | N    | Fe |
|------|------|------|------|------|------|------|------|----|
| ≤ 0.07 | ≤ 1.00  | ≤ 2.00 | ≤ 0.045 | ≤ 0.015 | 17.5–19.5  | 8.0–10.5 | ≤ 0.11 | balance |

Table 2 System specifications for laser beam welding

| model | Trumpl TruDisk 16002 |
|-------|----------------------|
| wavelength (nm) | 1030 |
| optical fibre diameter (µm) | 200 |
| collimation length (mm) | 150 |
| focal length (mm) | 300 |
| focal spot diameter (µm) | 400 |

Fig. 1 Experimental setup for round bar laser beam welding
Round bars with a diameter of 30 mm are used as specimens. The processing head is angled by 20° to prevent melt drop formation. The laser focus point is adjusted 4 mm below the specimen surface. Two flat nozzles provide argon shielding gas at 60 l/min flow rate at an angle of 45°. The distance to each other and to the specimen is 50 mm aiming above the specimen to reduce the keyhole’s gas plume and at the specimen bottom for cooling and melt drop prevention since the gas jet fans out. The general parameters have been determined by previous investigations [22–24] at 8 kW average welding power and 0.95 m/min welding speed.

**Experimental Procedure**

The welding parameters are varied between small, medium and high amplitude power $P_{\text{ampl}}$ and modulation frequency $f$, see Table 3.

The modulation depth $\Pi$ and normalised frequency $\Lambda$ are calculated according to (1) and (2). Welding starts at the average power and linearly increasing power output in triangular power modulation. Three specimens per parameter are analysed via scanning acoustic microscopy and one specimen per centre and corner parameters is analysed via metallographic cross section etched with Adler’s etchant for 5 s. For scanning acoustic microscopy (SAM) investigations, the specimens are cut longitudinally close to the weld seam and polished. The SAM-system (SAM 30, PVA TePla Analytical Systems GmbH, Westhausen, Germany) is used in a pulse echo mode and distilled water is used as a coupling medium for the ultrasonic wave energy. Treating the specimens with a thin layer of water-displacing penetrating oil prevents corrosion. An ultrasonic transceiver with a frequency of 75 MHz is used for the SAM investigations. A more detailed description is contained in [3].

**Experimental Results**

The results are divided into visual and metallographical weld inspection, SAM inspection, discussion.

**Table 3** Welding parameters for power modulation (left) and power scheme (right), average power: 8 kW, welding speed: 0.95 m/min, shielding gas: argon, gas flow rate: 60 l/min, bold x: metallographic analysis

| $\Pi$ | $P_{\text{ampl}}$ (kW) | $f$ (Hz) | 0.05 | 0.25 | 1.26 |
|-------|-------------------|---------|-----|-----|-----|
| 0.00  | 0                 |         |     | x   |     |
| 0.40  | $\pm$ 2           | x       | x   | x   |     |
| 0.67  | $\pm$ 4           | x       | x   | x   |     |
| 0.86  | $\pm$ 6           | x       | x   | x   |     |
Visual and Metallographical Weld Inspection

The outer weld appearance varies in dependence of the power modulation parameters, see Table 4.

With increasing amplitude power, the power cycles with their respective frequency can be recognised by periodically changing weld reinforcement, see Table 5.

Full penetration is achieved at all parameters, see Table 6. Without power modulation, a big melt pool forms in the specimen centre without containing any cracks or porosity. With power modulation, the central melt pool’s size generally increases and the amount of cracks and porosity increases with increasing amplitude power. The reason is an increasing weld depth with increasing modulation depth as described in literature [6, 12, 16]. The weld shape becomes irregular at a modulation frequency of 2 Hz, which is not favourable due to an increasing risk of weld defects.
SAM Inspection

Weld defects in the longitudinal plane are revealed by the SAM inspection, see Table 7. Pictures beside the keyhole plane with maximum amounts of defects are shown. The defects are mostly small pores and some small cracks according to the metallographic cross sections in Table 6. Without and with low power modulation, the amount of defects is low and increases at medium and high modulation depth. The increasing amount of defects does not agree with literature [6, 16, 17] and must be specific for welding round bars in a rotational process.

The weld pool structure and weld pool bulging can be recognised in the SAM micrographs’ keyhole plane since the weld pool partly solidifies as a network of cracks, if the laser beam is shut down without ramping it down, cf. [3]. The bright lines are bent at different degrees depending on the power modulation, see Table 8.

The bending degree is high without power modulation and decreases by about 30–100% with power modulation. The bending degree at 10 and 50 Hz modulation frequency is similar between 0.40 and 0.86 modulation depth. At a low frequency of 2 Hz, the bending degree decreases strongly with increasing modulation depth until the bulging is removed. During the period of reduced welding power the energy in the weld is reduced so far that bulging is effectively reduced and removed.
The results are summarised in Fig. 2. With increasing modulation depths at suitably low modulation frequencies, the induced periodical fluctuations of the weld depth increase. If also the power gradient or modulation depth during the power increase is high enough, the weld depth increases without recoil pressure induced bulge formation. Following, the weld depth is decreased during power decrease and increased again during power increase. At medium and high modulation frequencies, the induced weld depth change must be smaller since the bending degree reduction is smaller. In corresponding cross sections, the weld is straighter from the weld top to the root and it is not curved as without power modulation. In addition, the necking

| $\Pi$ | $P_{\text{amp}}$ (kW) | $f_{\text{mod}}$ (Hz) | 0.05 | 0.25 | 1.26 |
|-------|----------------------|------------------|------|------|------|
| 0.00  | 0                    | -                | 2    | 10   | 50   |
| 0.40  | $\pm 2$              | -                |      |      |      |
| 0.67  | $\pm 4$              | -                |      |      |      |
| 0.86  | $\pm 6$              | -                |      |      |      |

**Table 7** Exemplary inspection of longitudinal SAM images besides keyhole plane

| $\Pi$ | $P_{\text{amp}}$ (kW) | $f_{\text{mod}}$ (Hz) | 0.05 | 0.25 | 1.26 |
|-------|----------------------|------------------|------|------|------|
| 0.00  | 0                    | -                | 2    | 10   | 50   |
| 0.40  | $\pm 2$              | -                | 23°  | 30°  | 32°  |
| 0.67  | $\pm 4$              | -                | 10°  | 25°  | 30°  |
| 0.86  | $\pm 6$              | -                | 0°   | 32°  | 25°  |

**Table 8** Average bending degrees of weld pool indications (left) and measuring scheme (right)

**Discussion**

The results are summarised in Fig. 2. With increasing modulation depths at suitably low modulation frequencies, the induced periodical fluctuations of the weld depth increase. If also the power gradient or modulation depth during the power increase is high enough, the weld depth increases without recoil pressure induced bulge formation. Following, the weld depth is decreased during power decrease and increased again during power increase. At medium and high modulation frequencies, the induced weld depth change must be smaller since the bending degree reduction is smaller. In corresponding cross sections, the weld is straighter from the weld top to the root and it is not curved as without power modulation. In addition, the necking
region is moved or removed, see Table 6; Fig. 2. Accordingly, the separation of the top and bottom melt circulations is reduced. In result, the inherent depth and keyhole fluctuations can be influenced strong enough to control bulging and decrease the weld pool’s bending degree on the one hand. Gas bubbles are not trapped in the bulge anymore and the risk of cracks in the lately solidifying bulge decreases. On the other hand, the amount of weld defects increases with medium to high modulation depth since a mixing effect is introduced and the keyhole’s stability is reduced. The concept of depth saturation effects [10] is fully applicable only for power modulation in pulsed welding. In the present investigations, the amount of porosity should decrease with increasing modulation frequency because the duration of unstable welding mode would decrease, but the amount of porosity increases at a modulation depth of 0.67 in Table 7. As shown in previous investigations [3], the linear welding speed for round bars decreases from the specimen surface to the centre or from the weld top to the weld root. The melt pool dynamics in the weld root are very weak. With power modulation and the periodically changing weld depth strong melt pool dynamics are induced. By this mixing effect, degassing can be promoted in ordinary sheet welding because gas bubbles can combine and rise up more easily [16]. In high-depth welding of rotating round bars, degassing is impeded due to the specimen’s rotation, so only low modulation depths of up to 0.40 should be used to effect bulge reduction.
Conclusion and Outlook

Laser power modulation for rotational round bar welding has to be applied differently than for sheet metal. On the one hand, the amount of weld defects increases due to a mixing effect at medium to high modulation depths. Turbulences are brought into the weld root, where the melt flow is slower than at the round bar surface. On the other hand, weld pool bulging is reduced by applying laser power modulation. It can be completely impeded at low modulation frequencies and high modulation depths, but the amount of weld defects would increase due to the mixing effect. In conclusion, low modulation depths of up to 0.40 should be used to effect bulge reduction.

After discovering the differences between sheet and round bar welding with power modulation, further investigations about the influence of the modulation frequency on the keyhole stability and weld defects should be conducted using materials of poor weldability and modulation depths of up to 0.40.

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Data Availability The datasets generated and analysed during the current study are not publicly available but are available from the corresponding author on reasonable request.

Declarations

Competing Interests The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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