The influence of the gap size on the formation of a welded joint in hybrid laser-arc welding of angular joints and T-joints

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Abstract. In this paper, the influence of the gap width on the quality of the welded joint at the hybrid laser-arc welding of the angular and T-joints of 12.5 mm E36 shipbuilding plates without cutting the edges is considered. The results of experiments and the analysis of the cross-sections of the obtained welded joints were demonstrated. Microsections were analyzed in accordance with ISO 12932-2013 "Welding - laser-arc hybrid welding of steels, nickel and nickel alloys - Quality levels for imperfections", for internal, external defects and deviation from 90°. The table with classification of the analyzed samples to the classes ISO 12932-2013 is demonstrated.

1. Introduction

The first mention of laser-arc welding was made in 1978 [1]. Today, hybrid laser arc welding (HLAW) is widely used in different branches of industry: pipe industry [2, 3], shipbuilding [4], bridge-building [5], carriage engineering [6], aerospace industry [7] and others [8]. This welding method has advantages over conventional arc welding. The combination of two heat sources allows to weld a parts of large thickness without edge preparation, that significantly reduces the production cycle of the manufactured product.

The research of HLAW is important for determining the accuracy of mechanical pre-processing and assembly of samples for the quality welding of longitudinal seams in the pipe industry, joining of the panels in the shipbuilding and other areas of the heavy engineering industry.

At present, in the world, various experiments of welding of angular and T-joints have been made [9]. A complete, one-sided penetration of steel plates with a thickness of 8 mm without cutting edges was obtained. Also, the welding of plates with a thickness of 10 mm was carried out. For plates of this thickness, non-melting in the root of the seam was formed due to insufficient laser power. The modes and the welding scheme are presented. The gap in these research varied from 0 to 0.5 mm.

At the welding of 6 mm and 8 mm plates, it was found that welds without gap and with gap of 0.5 mm had a good external formation, but full penetration was not achieved (75% of the thickness) [10].

The angular deviation tests of samples [11] from shipbuilding steel KD-36 were carried out. The plate with thickness of 14 mm was welded to the substrate with a thickness of 21 mm. The samples were weld by double-sided hybrid laser arc and arc welding. The results were compared with each other. As a result, it was found that the seams welded by hybrid laser-arc welding have a smaller deviation angle, and high strength compared to arc welding. [12].
2. Experimental design

The aim of this research was the experimental investigation of the influence of the gap width on the quality of welded angular and T-joints.

For this requires, is needed to weld an angular joint with a variable gap from 0 to 1 mm and analyzing macrosections for defects. After analysis of the results, to weld the angular joint with a fixed gap width. Weld the T-joint with the best width of gap for the angular joint. The analysis of all samples corresponding to ISO 12932-2013.

The experiments were performed on a complex for hybrid laser arc welding made on the basis of an ytterbium fiber laser IPG LS 16, a wave length of 1065-1075 nm and a maximum laser radiation power of 16 kW. Arc source - EWM Phoenix 522 RC PULS Cold Arc with a maximum arc current of 520 A. Optical head Highyag Bimo with a focal length of 460 mm and a spot diameter at the focus of 0.23 mm. Welding angular torch Abicor Binzel MB 501D with a maximum current in the gas mixture 450 A.

The plates of shipbuilding steel E36 with thickness of 12.5 mm was used as material for the experiments. The chemical composition is shown in Table 1.

| Chemical Composition (wt %) |
|-----------------------------|
| C  | Si  | Mn  | Ni  | S   | P   | Cr  | Mo  | V   | N   | Nb  | Cu  |
|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| up to 0.18 | 0.15-0.9  | up to | up to | up to | up to | 0.05- | up to | 0.02- | up to | 0.4  | up to |
| 0.5 | 1.6 | 0.4 | 0.035 | 0.035 | 0.2 | 0.08 | 0.1 | 0.008 | 0.05 | 0.35 |

Sample dimensions: 200×70 mm. Cutting was done using laser. It was not any mechanically preparing the surface after laser cutting for welding. Power Pipe 60M was used as a welding wire (Table 2). A gas mixture Ar 80%+CO2 20% was used to protect of the liquid welding bath.

| Chemical Composition (wt %) |
|-----------------------------|
| C  | Si  | Mn  | P   | S   | Ni  |
|----|-----|-----|-----|-----|-----|
| 0.05 | 0.6-0.7 | 1.4-1.6 | <0.015 | <0.04 | <0.015 |

The position of heat sources and welded plates is shown in Figure 1. Before welding, a tick weld of plates was made.

The scheme is universal and suitable for welding angular joints or T-joints. The method of fixing the plates to the tooling is just different.

Preliminary experiments were carried out for the selection of process parameters previous to the experiments with variable of the gap. It was found that the gap and the power of laser radiation influence on the appearance of undercuts and “metal runout”. The wire feed speed does not reduced this defect. The appearance of non-melting zones depends on the gap and welding speed. It was found that at welding speeds...
above 20 mm s⁻¹ this defect obtained in 80% of the experiments. Based on this, the parameters presented in table 3 were selected.

### Table 3. Variable hybrid laser arc welding parameters.

| P, kW | Vₓ (mm c⁻¹) | Vₓₛ (m min⁻¹) | Iₑc (A) | Uₑc (V) | Stickout distance (mm) | Leading position of heat source | Distance between arc and beam (mm) | Gap (mm) |
|-------|-------------|----------------|---------|---------|------------------------|---------------------------------|---------------------------------|---------|
| 10    | 20          | 7              | 231     | 23      | 15                     | Laser                           | 4                               | 0.4-0.5 |

During the experiments it was found that the main defects in the welding of angular joints are undercuts ("leakage" of the weld metal) and non-melting.

### 3. Results and discussion

On the received regime, joint with a “divergent” gap from 0 to 1 mm was welded. The results of the experiment are shown in Figure 2. After tick-weld, the actual gap varied from 0.06 mm to 0.8 mm.

![Figure 2](image2.png)

During the measurements of the welded samples, it was found that the formation of large “metal runout” (more than 0.5 mm) of the weld metal begins with a gap of 0.6 mm. Therefore, further tests were carried out with a fixed gap of 0; 0.2; 0.4; 0.6 mm. Since the plates were after laser cutting completely zero gap could not be set. On the sample number 1, the gap was 0-0.1 mm over the entire length.

![Figure 3](image3.png)

**Figure 2.** Photo of macrosections obtained after welding a joint with a "divergent" gap (from 0.06 to 0.8 mm).

**Figure 3.** Sample 1, welding seam, weld gap up to 0.1 mm, A – front-side, B-reverse-side.
Figure 4. Sample 2, welding seam, weld gap of 0.2 mm, A – front-side, B-reverse-side.

Figure 5. Sample 3, welding seam, weld gap of 0.4 mm, A – front-side, B-reverse-side.

Figure 6. Sample 4, welding seam, weld gap of 0.6 mm, A – front-side, B-reverse-side.

Figure 7. Photos of macrosections with different weld gap (from 0 to 0.6 mm with step of 0.2 mm).
Figure 8. Microstructure of the seams: A - gap up to 0.1 mm, B - gap 0.2 mm, C - gap 0.4 mm, D - gap 0.6 mm.

The reason of non-melting at 0.4 mm gap (sample 3), at the root of the seam (Figure 8C) is not known. At previously experiments with same parameters, this defect was not observed. Also, there is no defect in a sample with a "divergent" gap.

In the course of the experiment, it was found that with a gap up to 0.1 mm (sample 1) there is no undercuts and a smooth border from the weld metal to the base material. With a gap of 0.2 mm (sample 2), an undercut was observed near the top plate. With a gap of 0.4 mm (sample 3), the upper undercut is increased and begins to form the lower. With a gap of 0.6 mm (sample 4), a large "metal runout" of the weld seam is observed, as well as extensive non-melting zones. The dimensions of the undercuts are shown in Table 4.

The T-joint was welded using the results of previous experiments (gap up to 0.1 mm). The base was the regime №3 (table 3). Welding was made in two passes to reduce welding deformations (Figure 9). After modeling of the process in Laser CAD (program for modeling the profile of penetration of a laser beam) [13, 14] was selected the power which providing depth penetration of welded plates on 60% - 70% - 6 kW (for both passes).

Figure 9. Two-pass welding of T-joints, without the edge preparation.

Before welding, the plates were fixed with four tick-weld, on both sides and at both ends. Based on the results of the welding of angular joints, a gap up to of 0.1 mm was set between welded plates.

Figure 10. Sample 5, welding seam, T-joint, A - first pass, B - second pass, red zone - gap of 0.3 mm (rough og edge surface after laser cutting).
An internal defect was found in the form of an elongated cavity. Perhaps this was due to the collapse of the vapor-gas channel. Probably, this defect can be avoided by increasing the diameter of the laser spot.

Measurements of external defects - undercuts - were made (table 4). Samples were classified according to the GOST (table 5).

**Table 4.** The measurements of undercut.

| sample number | 1   | 2   | 3   | 4   | 5       | 5       |
|---------------|-----|-----|-----|-----|---------|---------|
| Type joints   | angular | angular | angular | angular | T-joint, side A | T-joint, side B |
| Gap, mm       | 0    | 0.2  | 0.4  | 0.6  | 0.1     | 0.3     |
| Upper undercut (mm) | 0    | 0.24 | 0.51 | 0.16 | 1st pass = 0.16 | 1st pass = 0 |
|               |      |     |     |      | 2nd pass = 0  | 2nd pass = 0 |
| Lower undercut (9mm) | 0    | 0   | 0.11 | 1    | 1st pass = 0 | 1st pass = 0.05 |
|               |      |     |     |      | 2nd pass = 0.24 | 2nd pass = 0 |

**Table 5.** Classification of samples according to ISO 12932-2013.
Conclusions
In the course of the experiments it was found that with a gap up to 0.1 mm there is no undercuts and a smooth border from the weld metal to the base material. With a gap of 0.2 mm, an undercut was observed near the top plate, however, there is best classification according to ISO 12932-2013. With a gap of 0.4 mm, the upper undercut is increased and begins to form the lower. With a gap of 0.6 mm, a large "metal runout" of the weld seam is observed, as well as extensive non-melting zones.

With the T-joint, satisfactory formation of both weld beads was obtained. Consequently, a gap up to 0.1 mm is also optimal for welding T-joints.

It is necessary to carry out further studies on the elimination of gas pores at the root of the second pass of T-joints.

It is established that welding of angular and T-joints from steels of 12.5 mm thick by means of hybrid laser-arc welding can be carried out immediately after laser cutting, without preparing the edges and cutting.

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