The use of single-mode fiber laser for welding of stainless steel thin thickness

M V Larin\textsuperscript{2*}, Y B Pevzner \textsuperscript{1,2}, O I Grinin\textsuperscript{1,2} and I T Lasota\textsuperscript{1,2}

\textsuperscript{1}St. Petersburg State Marine Technical University, Lotmsanskaya Str. 3, St. Petersburg, Russian Federation
\textsuperscript{2}Peter the Great St. Petersburg Polytechnic University, Polytechnicheskaya str. 29, St. Petersburg, Russian Federation
\textsuperscript{*}E-mail address: xd.makc@gmail.com

Abstract. At this moment, solid-state lasers based on Nd:YAG are replaced by fiber ytterbium lasers. This is due to a number of advantages, such as: high electrical efficiency, long life of diodes for pumping, significant reduction in floor space, etc. In this regard, Nd:YAG laser was changed to YLR300 single-mode fiber laser manufacturing by IPG at the Rofin StarWeld 500 installation with scan head. Preliminary modes for welding stainless steel AISI 321 with a thickness of 0.1 - 0.4 mm were selected. In this report, the influence of the laser power and welding speed on weld geometry are presented. The welds were analyzed by optical microscopy. Lap welding of the heat exchanger-recuperator parts was carried out with the weld tightness test. Analysis of the experiments showed that the use of a single-mode fiber laser with scan head makes it possible to obtain high-quality seal welds of small thickness with a high productivity and welding speed on the order 250 mm/s.

1. Introduction
At manufacture of products in various industries big application is found by thin-walled designs. These include, for example, various heat exchangers, sensor housings and relays, membranes, fastening elements, and etc. Welding of various types of joints, such as, butt joint, end joint, lap joint and angle joint are applied for their manufacture. The thickness of the materials is usually from 0.2 to 0.6 mm.

Laser welding is one of rational ways small thickness welding. Focused laser radiation has a high energy concentration (E >10\textsuperscript{5} W/cm\textsuperscript{2}). It provides high rates of heating and cooling, a small volume of molten metal, and insignificant size thermal influence zone. It allows to minimize heating and welding deformation of structures.

The use of a laser heating source for welding metals of small thickness during through penetration excludes burn through and weld undercut due to the lack of mechanical impact on molten weld bath. The thermal cycle with high rates of heating and cooling makes it possible to significantly reduce the zone of thermal influence. It allows to reduce effect of the phase and structural transformations in an heat-affected zone leading to weakening, cracking, reduction of corrosion resistance, etc.[1]

The complexity is provided by the choice of optimum technological parameters of welding process (rate, power, pulse energy, beam diameter, lens focal length, focus arrangement concerning the machinable surface, duty cycle, and pulse frequency) to ensure a stable welding conditions and to obtain a quality joint. Many works are devoted to a research of small thickness welding from stainless steel [2, 3, 4] and to welding process model operation [5, 6, 7].
The purpose of this work is the research the laser welding conditions of small thicknesses to produce hermetic lap joints.

2. Equipment and materials
Currently, the solid-state and fibro-optical lasers generating radiation on a wavelength of 1 μm are widely used to laser welding. A distinctive feature of such lasers is that an optical fiber can be used to transfer of radiation to the working tool.

Fiber lasers displace Nd:YAG due to higher efficiency, longer service life, and smaller dimensions in modern industry. Fiber lasers retain the quality of the beam mode and the beam divergence at regulation of a power output in the considerable range due to the absence of thermal lens effect with a refractivity gradient in an optical resonator of the laser. It is especially important in cases where a high peak power is not required to perform a process operation.

In this regard, at the installation of the Rofin StarWeld 500 with Nd:YAG, the laser is replaced by a 300W single-mode ytterbium YLR300 laser. Figure 1 shows the emission spectra of the laser and the beam caustic.

![Emission spectrum measured by Anritsu MS9710A (a) and caustic of the laser beam (b).](image)

**Figure 1.** Emission spectrum measured by Anritsu MS9710A (a) and caustic of the laser beam (b).

Figure 2 shows StarWeld 500 with a video monitoring system of the working zone. Galvanometric scanner was used as a working tool, which ensures high accuracy and speed of moving the laser beam. The scanner is equipped with a fΘ-lens with a working field 110 by 110 mm.
Plates of steel (AISI 321) with a thickness of 0.2 mm and a size of 150 by 45 mm were used as samples for the experiment. The chemical composition of the steel is shown in Table 1.

### Table 1. Chemical composition of AISI 321.

| Chemical Composition (wt %) | C   | Si  | Mn  | Ni  | S   | P   | Cr  | Ti  |
|----------------------------|-----|-----|-----|-----|-----|-----|-----|-----|
|                            | up to | up to | 9.00- | up to | up to | 17.0- | 5xC- |     |
|                            | 0.08  | 1.00  | 2.00  | 12.00 | 0.030 | 0.045 | 19.0 | 0.80 |

3. Experimental design

The first stage of the work consisted in the theoretical estimation of powers range for laser welding with minimal evaporation.

The energy condition (1, 2), laser welding with minimal evaporation is achieved [1], was calculated as shown in equation:

\[
E_1 \leq E_{cn} \leq E_2, \quad (1)
\]

\[
E_1 = \frac{0.885T_m\lambda_r}{\sqrt{\chi \tau}} \quad E_2 = \frac{0.885T_b\lambda_r}{\sqrt{\chi \tau}}, \quad (2)
\]

where \(E\) = radiation power density, \(\chi\) = coefficient of thermal diffusivity (for stainless steel 0.056 cm\(^2\) / s); \(\tau\) = pulse duration; \(\lambda_r\) = the coefficient of thermal conductivity, \(T_m\) = the melting temperature of the material, \(T_b\) = the boiling point of the material.

The power density of \(E_{cn}\) will allow to determine the range of powers for laser welding. Laser YLR300 can set the minimum pulse width in 0.2 ms at a frequency of 3 kHz, with this pulse duration we get the power density range (3):

\[
7 \times 10^4 \leq E \leq 1.2 \times 10^5 \left(\frac{W}{cm^2}\right) \quad (3)
\]

The second stage of work, penetration on a plate 0.2 mm thick in two modes was executed in the calculated power range: pulse-modulated and continuous-wave welding. The following parameters were varied: power from 150 to 300 W, speed from 100 to 500 mm / s. Cross-section of seams were analyzed by optical microscope. Optimal mode was chosen based on obtaining no defects.

The third stage, two overlapping plates were welded on the previously selected modes. It is important to provide contact of plates of small thickness when welding with an overlap, as even a slight gap can

![Figure 2. Rofin Starweld 500 (a) and scanner (b).](image-url)
lead to weld defects. Cross-section has been made from the received seams. Analysis of the sections was carried out using an optical microscope. Figure 3 shows the scheme of the experiment.

![Figure 3. Schematic diagram of experimental setup.](image)

The last stage of work heat exchanger details from steel (AISI 321) were welded for receiving a tight joint.

4. Results and discussion

4.1 Pulse mode

Figure 4 shows photos of seams cross-section and their appearance. The radiation was generated at a frequency 3 kHz and a pulse duration of 0.2 ms. The spot size was 0.1 mm.

![Figure 4. Cross section of 200 μm stainless sheet and views of welding seam: 1: P (average) = 95W, V = 100 mm/s; 2: P = 95W, V = 150 mm/s; 5: P = 140W, V = 250 mm/s.](image)

In difference from the continuous radiation use of pulse radiation ensures a minimum heat input in the part. Welding with a lower heat input affects the microstructure to a lesser extent and reduces the likelihood of deterioration of the corrosion resistance of the welded joint.
Seams obtained in modes 1 and 2 have defects in the form of spatter on the surface of the seam and undercut. Increasing power and speed contribute to reducing the amount of spray and the depth of the undercut. The absence of top bead on the surface indicates that there is no intensive evaporation during the welding process, which is typical for the pulsed regime.

4.2 Continuous-wave mode
Figure 5 shows photos of seams cross-section and their appearance. The radiation was generated in a continuous mode. The spot size was 0.1 mm.

The use of continuous generation requires careful selection of parameters, due to the increase in the amount of heat deposited in the welded material, which can lead to welding deformations. Using a single-mode laser allows to receive a laser spot of small size with high radiation quality (M2 = 1.05). Figure 5 shows quality seams without defects and with minimal welding deformations at high welding speed.

Welding in the continuous wave mode gives stabler formation of a seam at an identical running energy deposition (P/V) in the modes No. 1 and No. 8. In contrast to the pulsed mode, the beads on the seam are present on both sides. This indicates that in the process of welding a keyhole appears. Also crater is at the end of the seam, it is formed after a radiation stop as a result collapse of the keyhole.

4.3 Overlap welding
As shown above, continuous welding generates more stable joints and no defects. Therefore, this method was chosen for welding two plates with a thickness of 0.2 mm overlap. Figure 6 shows the results of welding.
Figure 6. Cross section of two thin sheets and views of welding seam: 11: P = 300W, V = 300 mm/s; 12: P = 300W, V = 250 mm/s; 13: P = 300W, V = 200 mm/s

A slight (~ 0.02 mm) gap between the welded plates formed during welding did not affect the quality of the welded joint. The structure does not have anisotropy, the phase composition in comparison with the parent metal has not changed, and HAZ is absent.

4.4 Heat exchanger welding
According on the studies, mode No. 11 was used for welding heat exchanger parts (0.2 ± 0.2 mm)/Figure 7 shows this heat exchanger. Leak test of a joint weld by method of kerosene test showed a positive result.

Figure 7. Heat exchanger-recuperator.

5. Conclusions
The laser welding of stainless steel small thicknesses (0.2-0.4 mm) using a single-mode laser was analyzed. Regions of modes with high speed (up to 300 mm / s) for pulsed and continuous welding
modes were determined. The best results on the formation of the seam and the absence of defects showed welding in continuous mode. Welding of the heat exchanger parts, which passed the kerosene test, was made.

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