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DEVELOPMENT OF AUTOMATED LASER WELDING TECHNIQUE AND EQUIPMENT FOR MANUFACTURING PARTS OF HEAT EXCHANGERS FOR MARINE VESSEL ENGINES

Equipment for laser welding complex, which can apply to machine-building, aerospace, shipbuilding, and automobile industries, has been designed and manufactured on the basis of technique for automated laser welding of flat tubes made of copper-nickel alloys. A method for controlling the integrity of welded flat tubes has been developed. It implies the pressure tests and the search of defective sections by laser interferometry technique in automated mode. A specialized welding head has been designed and manufactured for industrial application of laser welding technique.

Key words: marine heat exchangers, copper-nickel alloys, laser welding, slitting compounds, and pulse-modulated radiation.

The heat exchangers apply to remove heat from the power plants (for instance, engines) of marine vessels with the use of overboard seawater as cooling agent. The main working part of these devices is a figured flat thin-walled tube made of copper-nickel alloy. These metal tubes run into a tube plate by welding or brazing. The need to use copper-nickel alloys for manufacturing these heat exchangers is dictated by working conditions: the heat exchangers must be highly resistant to corrosive effect of seawater. Welded or brazed connections should have high strength and complete impermeability under prolonged operation at high temperatures in aggressive environments.

Welding is a dominating method for the manufacture of heat exchangers. It ensures higher reliability and does not require expensive solders. According to experts of *ATIS-Lab*, today, the laser welding is one of the most promising methods for heat exchanger welding [1]. For example, it is used for the manufacture of *Alfa Laval Compabloc* CP 30, CPL 40, CPL 50, and CPL 75 heat exchangers [2]. The plates and tubes of different heat exchanger models are made of stainless steel, titanium, titanium-palladium alloy, Hastelloy and so on. The use of laser welding has made it possible to get narrow and thin welds on these materials, to alleviate significantly the total thermal effect on the device, and to reduce its susceptibility to cyclical and thermal loads. The laser welding improves reliability, increases service life, and makes it possible to exploit the *Compabloc* heat exchangers in harsh conditions. Among other advantages of laser welding there are the automation of process and the reduction of time of heat exchanger manufacture.

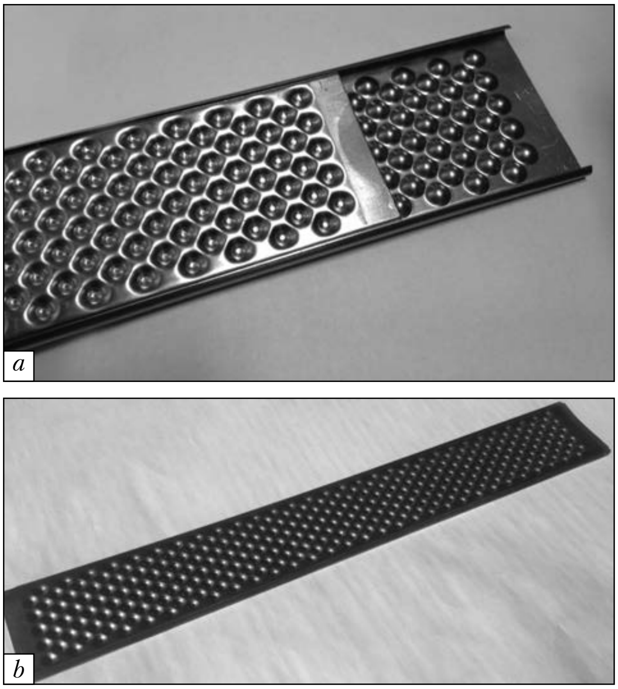

Fig. 1. Appearance of blanks (*a*) to be welded for the manufacture of heat exchanger tube (*b*)

The authors of [3] proposed to replace brazing by laser welding for the manufacture of thin-walled cooling panels and heat exchangers in connection with high requirements applying to this equipment that operates at high pressures, high temperatures, and repeated thermal cycling. Welds of satisfactory quality able to withstood pressure up to 10 MPa were obtained for welding of stainless steels, nickel alloys, and titanium alloy VT15.

According to *Lazerform,* the laser welding technique has been used successfully for welding of thin-walled tubes with a wall thickness of 1 mm made of structural steels and titanium alloys. These tubes are used to produce heat exchangers for the nuclear industry, which requires particularly high reliability [4]. The strength of the welds is compared to that of the parent material, whereas the resistance to corrosion and to the formation of hot and cold cracks increases.

However, the laser welding technique can be improved using pulse modulation of laser radiation. This approach gives fine-grained and fine-powder structure of weld's molten metal and makes it possible to minimize its width and heat affected zone (HAZ). The compounds having these parameters are capable of providing not only high strength, but also high impact hardness, elongation, corrosion resistance and so on. The proposed approach is of crucial importance, insofar as the heat exchangers with such characteristics can operate under high temperature, pressure, and are resistant to the corrosive effects.

Given the above, the task of this research was to create a technique for automated laser welding of copper-nickel parts of heat exchangers used for cooling of marine vessel engines with overboard water. The other task was to design and to manufacture laser welding equipment based on the developed technique, which can be implemented in mechanical engineering, aerospace, shipbuilding, and automotive industries.

To address the above tasks a research was carried out on copper-nickel samples (MN25 alloy) having a thickness $\delta = 0.35$ mm using a fiber laser YLR-400-AC (*IPG*, Germany) with a wavelength of $\lambda = 1.07$ μm and a radiated power of up to 400 W. Since the flat tubes of heat exchanger consist of two parts connected to each other not only on the edges, but also across the whole length (Fig. 1), the welding was made by slot spot and linear seams. Among the criteria of weld quality there were not only the absence of pores, full penetration welding, high-quality formation of reinforcing beads, but also the achievement of strength and tightness of connections at air pressure inside the tube up to 0.6 MPa (according to the specifications). It was found that for addressing this problem the structure in the welds and HAZ should be as fine-grained as possible. It can be prepared in various ways.

For example, the authors of [5] proposed to use nano-powder modifiers (TiN, TiN + Cr, mixture of Y_2O_3 and TiNi and make it possible to change the weld chemical composition while reducing the weld structure to very small particles, which contributes to a significant enhancement of weld mechanical properties. A more simple way to ob-

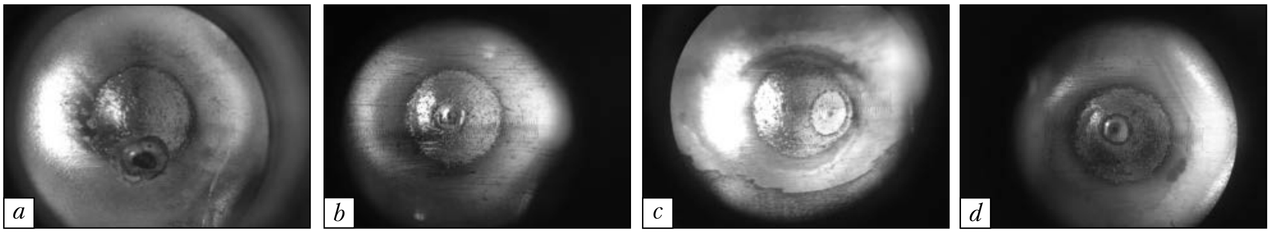

Fig. 2. Development of technique for laser welding by slot welds (MN25 alloy, δ = 0.35 mm): *a* – wormhole (surface blowhole); *b* – partial penetration weld (incomplete penetration); *c* – beam deflection from the center of the hole; *d* – high-quality weld

tain fine-grained structures is to use pulse-periodic modulation of laser radiation.

The authors of [6] developed a method for laser welding of metals based on the action of laser radiation with a pulse of complex shape on the surface of welded metal. For this purpose, it was proposed to melt the metal locally, in the welding zone, by pulses of focused laser radiation, which had a steep leading edge and a smoothly decreasing trailing edge.

In this case, the trailing edge of the pulse comprises two inclined sections. The upper one ensures fusion of welded metal without intense evaporation, while the lower one gives the weld a fine-grained structure by creating conditions for the emergence of the maximum number of crystallization centers and minimization of linear growth rate of crystals in welded metal. The lower section is modulated by frequency of ultrasonic range with an amplitude ensuring a required slope of the section and fluctuations of the weld pool. The introduction of ultrasonic vibrations occur without an additional vibrator.

The proposed method of laser welding underlies the technique for automated laser welding of parts of marine vessel engine heat exchangers made of MN25 alloy (δ = 0.35 mm) by slot spot and linear (length 350 mm) welds.

When developing the laser welding technology, such specific physical properties of MN25 copper-nickel alloy as propensity to gas absorption, due to the presence of nickel, at elevated temperatures and high sensitivity to impurities were taken into consideration. These properties could lead to the formation of internal pores and crystallization cracks. To eliminate these defects the following preventive measures were implemented: laser scanning, selection of heat input, and protection of weld pool and weld by inert gas (argon). It was found that to obtain high-quality welds it was necessary to clean thoroughly the welded edges and the adjacent areas (having a width of 20—25 mm) by mechanical means (to remove a sulfur tarnish) and to degrease them in acetone, white spirit or petrol. Insofar as for preventing the edges from the formation of wormholes, they should fit flush with each other, the blanks were previously straightened.

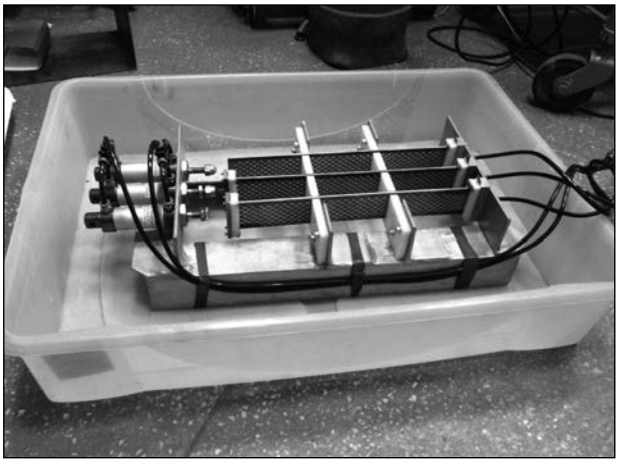

Fig. 3. Test bench for strength and tightness tests of heat exchanger tubes

In the course of experiments on laser welding of MN25 alloy by the slot spot weld it was found that among the characteristic defects there were wormholes, incomplete penetration, and deviation from the center of the hole (Fig. 2). The ex-

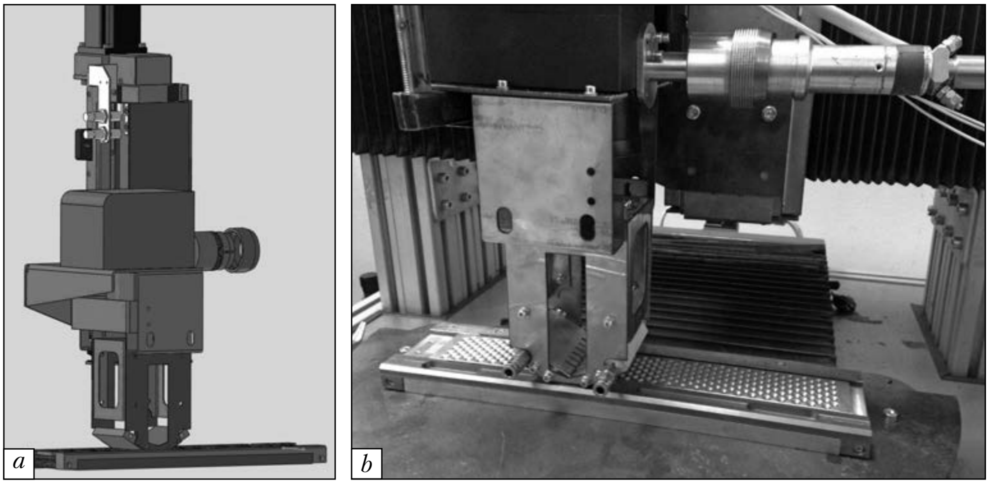

Fig. 4. Design (*a*) and appearance (*b*) of shielding gas system for simultaneous protection of multiple laser welding zones

pansion of weld spot diameter by increasing the focal spot impaired hydrodynamic stability of the weld pool and caused its drooping or formation of wormhole. These could be explained by uneven heat dissipation from the zone of welding (loose fit of the upper and the lower pieces) and uneven heating as a result of beam deflection from the center of the hole. In the case of the slot linear welds the wormholes were reported for loosely fitted pieces, while the incomplete penetration was caused by insufficient heat input of laser welding. As a result, it was established that the average heat input should be 20—22 J/mm and the shielding gas consumption should account for 6 l/min.

A test bench was designed to verify the results of technique developed. It allowed the operators to test three tubes simultaneously (Fig. 3). For this purpose, three pneumatic cylinders through the seal coupling pressed the sample to the opposite coupling; then compressed air was fed into the submersed tubes. Each tube was tested for leaks by air pressure of, at least, 0.6 MPa being submersed in water for one minute. The quality of welded samples was controlled by searching for the defects during the pressure test on the bench (see Fig. 3). For the purpose of automatic control a laser interferometry technique was used [7].

In order to apply commercially the proposed technique for laser welding of heat exchanger flat tubes, a new technical solution of shielding gas system design was developed (Fig. 4). In this design, a protective nozzle (a kind of slit located transversely to the longitudinal axis of the part) was slightly wider than the welded part. In the middle of the nozzle, there were protective clamp bars with holes for getting the focused radiation in the zone of welding. On both sides of the bars, there were tubes with holes through which shielding gas (argon) fell into the zones of laser welding. The laser radiation "performed" slot spot welding with the help of high-speed inertia-free two-coordinate positioning system, with the protective nozzle shifting linearly along the axis of the welded part.

Hence, among the project outputs there are:

- Technique for laser welding of copper-nickel alloy MN25 (δ = 0.35 mm) by slot spot and linear welds with pulse modulation of radiation;
- Method for control of welded samples, which includes pressure test of the sample and search of defects by laser interferometry method in automatic mode;
- Special welding head for the industrial application of developed laser welding technique.

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РАЗРАБОТКА ТЕХНОЛОГИИ И ОБОРУДОВАНИЯ АВТОМАТИЗИРОВАННОЙ ЛАЗЕРНОЙ СВАРКИ ДЛЯ ИЗГОТОВЛЕНИЯ ДЕТАЛЕЙ ТЕПЛООБМЕННИКОВ СУДОВЫХ ДВИГАТЕЛЕЙ

На основании разработанной технологии автоматизированного лазерного сваривания плоских трубок из медно-никелевых сплавов спроектировано и создано технологическое оснащение лазерного сварочного комплекса, которое может быть внедрено на предприятиях машиностроительной, авиакосмической, судостроительной или автомобилестроительной промышленности. Для контроля герметичности сварных плоских трубок разработана методика, заключающаяся в испытании образцов давлением и поиске дефектных участков лазерной интерферометрией в автоматизированном режиме. Для промышленного применения разработанной технологии лазерной сварки спроектирована и изготовлена специализированная сварочная головка.

Ключевые слова: судовые теплообменники, медно-никелевые сплавы, лазерная сварка, прорезные соединения, импульсная модуляция излучения.

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РОЗРОБКА ТЕХНОЛОГІЇ ТА ОБЛАДНАННЯ АВТОМАТИЗОВАНОГО ЛАЗЕРНОГО ЗВАРЮВАННЯ ДЛЯ ВИГОТОВЛЕННЯ ДЕТАЛЕЙ ТЕПЛООБМІННИКІВ КОРАБЕЛЬНИХ ДВИГУНІВ

На підставі розробленої технології автоматизованого лазерного зварювання плоских трубок з мідно-нікелевих сплавів спроектовано і створено технологічне оснащення лазерного зварювального комплексу, яке може бути впровадженим на підприємствах машинобудівної, авіакосмічної, суднобудівної або автомобілебудівної промисловості. Для контролю герметичності зварених плоских трубок розроблена методика, яка полягає у випробуванні зразків тиском і пошуку дефектних ділянок лазерною інтерферометрією в автоматизованому режимі. Для промислового застосування розробленої технології лазерного зварювання спроектована і виготовлена спеціалізована зварювальна головка.

Ключові слова: судові теплообмінники, мідно-нікелеві сплави, лазерне зварювання, прорізні з’єднання, імпульсна модуляція випромінювання.

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