УДК 621.791.75: 629.5.024

DESIGNING OF THIN SHEET PLATING SHIP CONSTRUCTIONS FROM ALUMINUM ALLOYS WITH MINIMIZATION OF LOCAL WELDING DEFORMATIONS

ПРОЕКТУВАННЯ ТОНКОЛИСТОВИХ СУДНОВИХ КОРПУСНИХ КОНСТРУКЦІЙ З АЛЮМІНІЕВИХ СПЛАВІВ З МІНІМІЗАЦІЄЮ МІСЦЕВИХ ЗВАРЮВАЛЬНИХ ДЕФОРМАЦІЙ

DOI https://doi.org/10.15589/smi2019.1(11).2

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Abstract. In low-tonnage shipbuilding in the manufacture of hull structures made of aluminum alloys, the main method of joining parts is argon-arc welding. However, the high deformation capacity of structural aluminum alloys causes the occurrence of local welding deformations that impair the performance and appearance of the structure. Elimination of residual deformations by editing is associated with significant material and energy costs and does not always ensure satisfaction of the high requirements imposed on the presentation of the product. Therefore, the design of such structures should provide for the possibility of their manufacture with minimal labor input and deformations not exceeding the allowable values. The developed technique provides for the design of typical hull structures of pleasure motor yachts according to the Rules of classification societies or ISO12215-5 standard taking into account technological measures to minimize local welding deformations of thin sheet plating from welding set. Using the example of designing various types of hull structures made of alloy 5083H111, the sequence of selecting the thickness of the section plating, the parameters of the cell of the set, the type and size of welds, ensuring the strength requirements established by the Rules and reducing the residual welding deformations to the allowable limit, is shown. To implement the welding technology, an original design of a welding torch with in-nozzle transverse oscillations of the electrode wire was proposed to reduce the energy introduced into the weld. The torch can be used for mechanized and automatic pulse-arc welding.

Key words: design, aluminum alloy, technology, welding deformations, low-frequency oscillations of the electrode.

Анотація. У малотоннажному суднобудуванні у процесі виготовлення корпусних конструкцій з алюмінієвих сплавів основним способом з'єднання деталей є аргонодугове зварювання. Однак висока деформаційна здатність конструкційних алюмінієвих сплавів зумовлює виникнення місцевих зварювальних деформацій, що погіршують експлуатаційні характеристики і зовнішній вигляд конструкції. Усунення залишкових деформацій правкою пов'язане зі значними матеріальними й енергетичними затратами і не завжди забезпечує задоволення високих вимог, що пред'являються до товарного вигляду продукції. Тому проектування таких конструкцій має передбачати можливість їх виготовлення з мінімальною трудомісткістю і деформаціями, що не перевищують допустимих значень. Розроблена методика передбачає проектування типових корпусних конструкцій прогулянкових моторних яхт за Правилами класифікаційних товариств або стандарту ISO12215-5 з урахуванням технологічних заходів щодо мінімізації місцевих зварювальних деформацій тонколистової обшивки від приварювання набору. На прикладі проектування різних типів корпусних конструкцій яхти зі сплаву 5083H111 показана послідовність вибору товщини обшивки секцій, параметрів осередку набору, типу і розмірів зварних швів, що забезпечують встановлені Правилами вимоги щодо міцності і знижують до допустимого рівня залишкові зварювальні деформації. Для реалізації технології зварювання запропонована оригінальна конструкція зварювального пальника із внутришньосопловими поперечними коливаннями електродного дроту, що сприяють зниженню енергії, яка вводиться у зварний шов. Пальник може бути застосований при механізованому та автоматичному імпульсно-дуговому зварюванні.

Ключові слова: проектування, алюмінієвий сплав, технологія, зварювальні деформації, низькочастотні коливання електрода.

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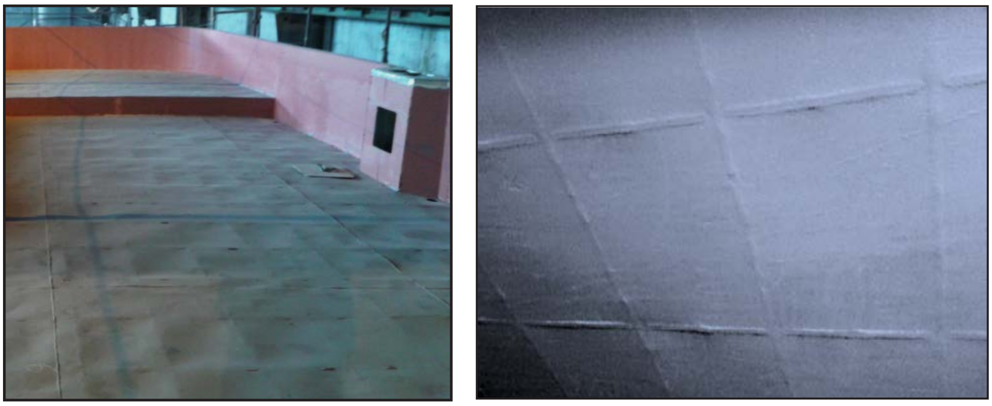
Problem statement. Modern manufacturing technology of thin-sheet hull structures of ships from aluminum alloys provides for the connection of parts using arc welding. If the design of structures does not take into account the effect of welding and / or no rational manufacturing process is chosen, then the residual welding deformations exceeding the permissible values are a negative consequence. These deformations not only reduce the bearing capacity of structures and increase the hull's resistance to movement, but also degrade the appearance of the vessel as a whole (Fig. 1).

To eliminate residual welding deformations and impart a “marketable” design, such corrective measures are often used, such as post-welding thermal straightening and / or filling of the section shell [1−3]. However, these measures, despite their high cost, do not always guarantee obtaining an acceptable result, therefore, the design of new structures should be carried out with regard to



a b

Fig. 1. The appearance of the hull structures of the pleasure yacht made of aluminum alloy 5083*H*111 after welding: a – shell of deck; b – shell of bottom

Table 1. Deformation of the shell from the plane between the frames, mm

Construction element		By standard [10] (for spacing 300–1000 mm)		Factual data
		Recruitment	Limit value	
Shell	Cylindrical part (side and bottom shell)	4	8	5–10 7,5
	Bow and stern	5		3–7 5
Design Deck	In the cylindrical part	4	4	5–10 7,5
	Bow and stern	6	6	3–7 5
Superstructure Deck	Open area	4	4	5–30 17,5
Shell of Superstructure	Outside area	4	4	5–15 10

their manufacture with minimum labor-intensiveness and minimum allowable welding deformations meeting the requirements of the quality standard DSTU ISO 9001: 2015. Therefore, the development of methods for designing thin-sheet hull structures, allowing to reduce the cost of their manufacture is an actual task.

Latest research and publications analysis. It is well known that when designing ships, compliance with the requirements of the Rules of various classification societies [4; 5] ensures the necessary level of operational reliability of the design under development [6–9]. However, as the experience of building low-tonnage vessels, including yachts made of aluminum alloys, even if the sequence of stitching, as provided by the design documentation, often does not provide an acceptable level of local deformations of structures after welding [10].

Measurements of the surface shape of the hull structures made of aluminum alloy 5083*H*111 carried out at the production show a significant excess of residual deformations over the allowable values (table 1). The cause of warping of the plating is the loss of stability of thin-sheet plating from the longitudinal shrinkage of fillet joints connecting the reinforcing frames with the plating. The implementation of technological measures to reduce welding deformations requires, as indicated above, additional costs and time.

Therefore, it is advisable at the design stage of the hull structure to provide for its structural design so that measures to combat welding deformations are provided [2; 3]. This should take into account the known recommendations on the appointment of types of welds, contributing to the reduction of residual volumes of plastic deformations shortening, which are as follows [3].

In the frames welded T-joints with frames and shell, the seams in which the calculated seam leg exceeds the minimum, technologically feasible size must be made continuous.

When seams are assigned by calculation, preference should be given to continuous two-sided seams. For joints that are not calculation for strength, a minimum, technologically feasible joint should be assigned. With the same minimum seam leg, the use of intermittent seams is more advisable than continuous.

Ratio of residual volumes of longitudinal shortening of welded T-joints with continuous and intermittent equal strength seams [2]

$$\frac{V_{con}}{V_{int}} = \frac{K_{con}}{K_{int}}, \qquad (1)$$

где V_{con} и K_{con} – the volume of the longitudinal shortening and the legs of the continuous seam, respectively; V_{int} и K_{int} – the same for intermittent seam.

Volumes of longitudinal shortening are calculated by the formulas:

for continuous seam

$$V_{con} = v \cdot L = 0,29 \frac{\alpha}{c\rho} q_l L , \qquad (2)$$

for intermittent seam

$$V_{int} = v \cdot L \cdot \frac{l_{int}}{p_{int}} , \qquad (3)$$

Here v – linear longitudinal shortening; L – length of the seam; $\frac{\alpha}{c\rho}$ – metal deformation coefficient; q_l – linear heating energy of the welded elements; l_{int} и p_{int} – weld length and intermittent weld pitch, respectively.

And, finally, in order to reduce local deformations of the shell from welding of the frames, its thickness should be increased or the distance between the frames should be reduced.

Separation of previously unsettled parts of the general problem. The fulfillment of the above requirements and recommendations is reflected separately in the design documentation for the design of hull structures and in the process documentation for their manufacture. A comprehensive solution to the problem of reducing the time and material costs of creating competitive products in yacht building can be implemented using an improved methodology for designing hull structures of yachts, taking into account modern technological recommendations for reducing welding deformations.

The article aim – development of a design methodology for hull structures and superstructures of aluminum alloy yachts according to the requirements of the Rules of classification societies, taking into account the welding technology, ensuring minimal local deformations from the welding frames.

Methods, object and subject of development. During the development of the methodology, the calculation methods of structural mechanics of the ship, the calculation and design of welded joints, the calculation of welding deformations and stresses, and the design of arc welding technology were used.

The object of development are the bottom, side and deck sections of motor yachts made of aluminum structural alloy, **the subject** of development is the thickness of the sections shell, the type and size of welds connecting the frames with the plating, welding technology.

The basic material (results). For the development of the design methodology, typical designs (floors) of ten different single hull motor yachts with a small hull extension were chosen, i.e. for which the ratio $L / B < 6$ (here L is the hull length; B is its width) ... For selected the indicated ratio of the parameters is: L / B = (8,5…29,8) / (2,4…6,9) = 3,5…4,3. All hull structures are made of aluminum-magnesium alloy 5083*H*111 (analogue alloy AlMg 4,5).

Structural design was performed in accordance with the requirements of the standard [4] in the following sequence:

1) determined the design load for each type of floors. The width of all floors was limited in the transverse direction by the distance between bulkheads or frame frames. The length of the floors was taken depending on the type:

– for bottom floors – half-width of the hull, from CL to side, with bearing on board and on keel to CL;

– for side floors – the distance from the deck to the shear with the support on the deck and cheekbone;

– for deck floors – hull half-width – from CL to board with bearing on board and Carlings in CL.

2) chose the layout of the beams and make up the appropriate design scheme of floors with the transverse frames system;

3) the required thickness of shell was calculated;

4) determined the required moments of resistance and the height of the frames section;

5) chose sections of welds;

6) checked the calculated thickness of the shell for the absence of buckling deformations.

When designing, the authors took into account the constructive and technological recommendations developed by the authors aimed at reducing the residual welding deformations:

− reinforcement frames profile − T-beams (if the length of the hull of the yacht is L > 12 m) or strips with a wall thickness equal to the thickness of the outer shell (if $L \leq$ 12 m);

− the frames is shell welded by the mechanized method with a solid electrode wire with continuous two-sided seams (connection − T3 according to GOST 14806-80);

− the leg of the corner seams, ensuring equal strength of the seam and the base metal, is determined by calculation and is selected according to the Rules [6 – 9]. If, according to the calculation, a leg less than 4 mm is required, the frames is welded with intermittent 4 mm long leg chain seams. The pitch and length of the seam sections are determined in accordance with the Rules [5];

− in order to reduce the heat energy of welding, reduce the volume of longitudinal plastic deformations and ensure high dimensional stability of fillet welds, the welding is performed using a pulsed arc method using standard or specialized equipment, for example [11];

− from the condition of ensuring free access to the welding seams, the smallest distance between the beams (space) is limited to 300 mm.

In order to establish general design requirements for the design of typical sections of the yacht, as well as the development of recommendations for the selection of parameters of welded joints to minimize local deformations of the shell, the hull and superstructure of the yacht were divided into zones within which different register loads act (Fig. 2). For each of the zones, according to the Rules, the limiting values of the shell thickness, the spacing frames, the type and size of the fillet seams of the welding frames to the shell are frames. Each zone corresponds to the parameters available at the design and / or design stage, which can be varied to minimize deformations in the visible part of the hull structure and superstructure of the yacht.

For each type of sections included in a specific zone, in accordance with the requirements of the Rules, calculated by the formulas (1) – (3) the allowable intervals for changing the parameters of the welds of the welding frames to shell depending on the size of the space and the length of the yacht's hull and the corresponding nomograms (Fig. 3).

Nomograms also allow you to assign a spacing size depending on the required thickness of the shell, if there is no deformation, buckling resistance from welding the frames with continuous or intermittent seams with a 4 mm leg.

If the calculated seam leg exceeds 4 mm, then the intermittent seam should be replaced with a continuous two-sided with a leg equal to the calculated one. In this case, constructive measures aimed at minimizing welding deformations are limited to changes in the thickness of the space, the size of the installation and the ratio of the sides of the support contour.

For each specific spacing size, with a fixed length of the welded section, there are maximum and minimum spacing of a discontinuous seam, which are calculated using formula (3) and are shown on the nomograms by double solid lines.

The thick solid lines on the nomograms, calculated on the basis of the Rules, correspond to the maximum allowable step of the intermittent welding, which has the necessary strength to ensure the strength connection between the shell and the frames, perceiving the load specified, for example, in Rules [5] and etc.

The dashed lines on the nomograms indicate the minimum permissible pitch of the intermittent weld seam, which, with a given spacing and thickness of the cloth, does not lead to loss of stability of the casing.

All pitch values of the intermittent weld, which lie above the corresponding curve, are then safe. Therefore, using the above nomograms, the range of allowable values can be narrowed when selecting the parameters of a intermittent weld of the frames to the shell.

The algorithm for the design of a hull structure is as follows:

If the design of the yacht is carried out in accordance with the Rules in which the size of space is regulated, for example [5] or the Shipping Register of Ukraine, then the calculation of normal space is performed. Focusing on the size and allowable spacing of the normal spacing for the appropriate type of floors (deck, side, bottom), several possible combinations of spacing (usually a multiple of 10) and its corresponding thickness of shell, regulated by the Rules, multiple to the rolled stock range should be determined. Then you should proceed to work with nomograms.

If the design is performed according to the Rules [6–8], in which the packing size is not directly regulated by the load, immediately after assigning the distance between the beams of the main frames and determining the required plating thickness according to the Rules, proceed to work with nomograms.

The work with nomograms (see Fig. 3) is performed in accordance with the developed key as follows.

For the found combinations “space – thickness” we find the areas of permissible values bounded by curves at bellow (dashed lines), corresponding to the absence of buckling of the casing from welding of the frames, and from the top by curves (solid lines) corresponding to the required bearing capacity of these welds of the frames for this type floors. The final choice of seam parameters within the range of allowable values is carried out by comparative analysis of several suitable combinations,

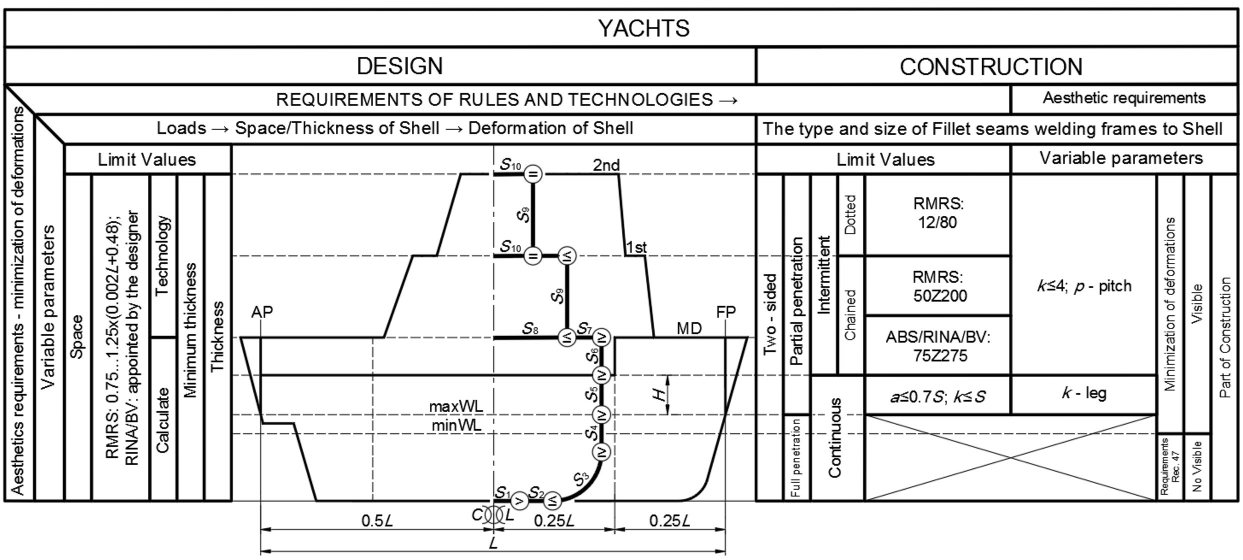
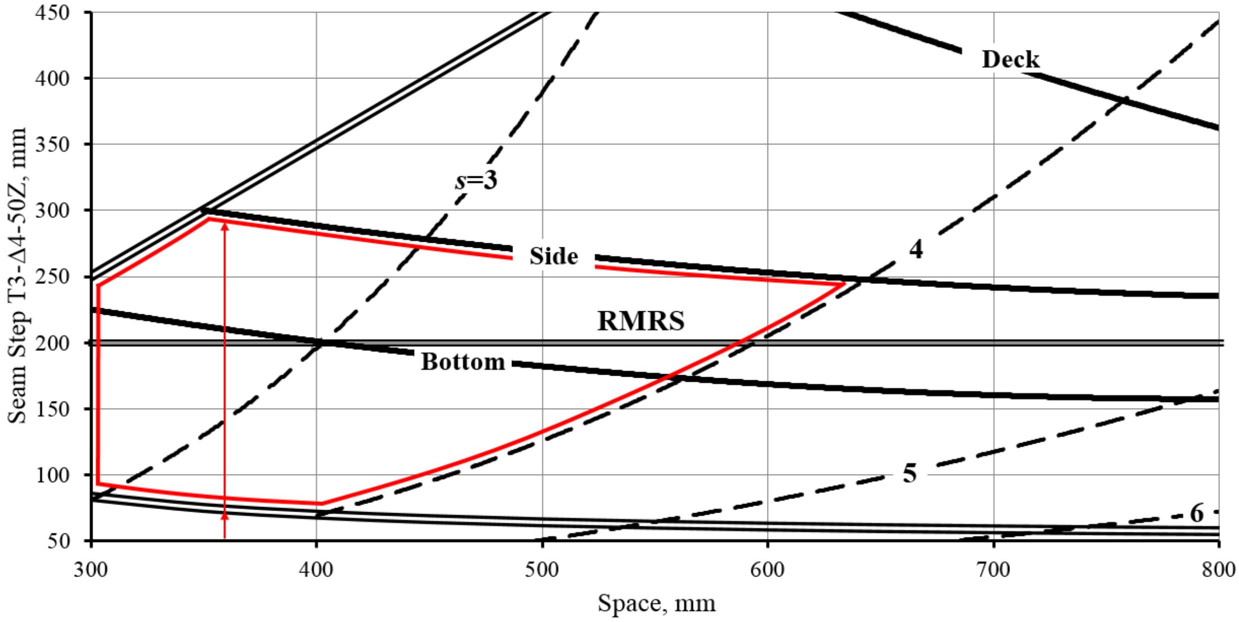
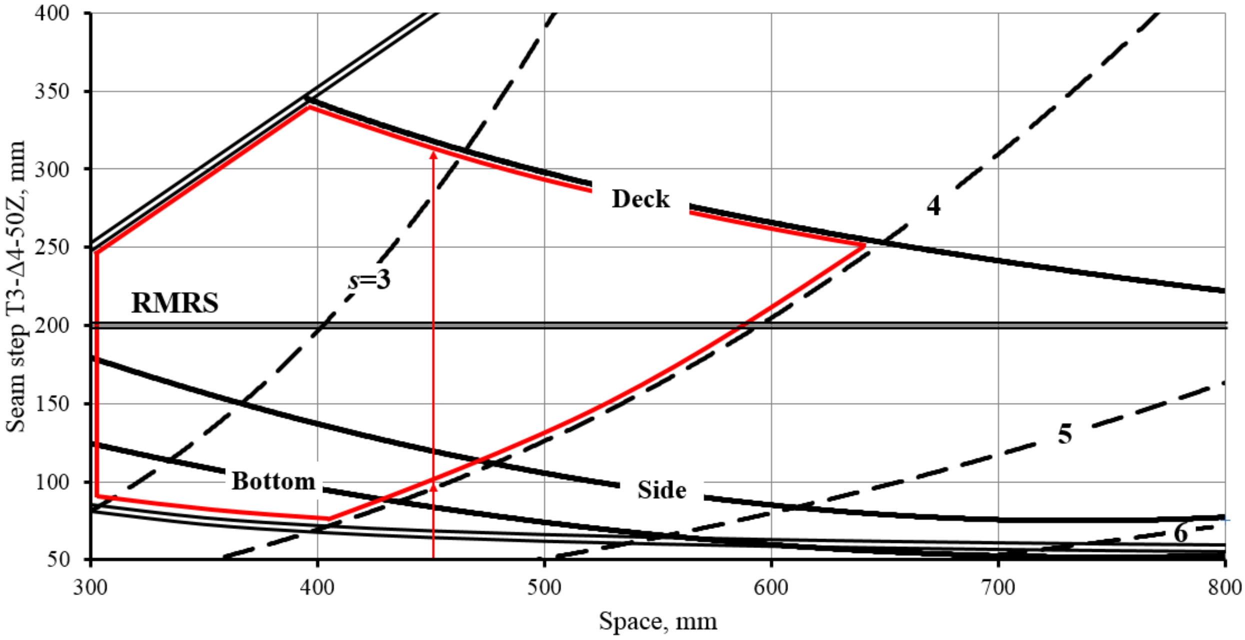


Fig. 2. The mnemonic scheme of the design development and welded joints of the hull sections of the yacht, taking into account minimization of local welding deformations



a



b

Fig. 3. Nomograms for determining the permissible values of weld seam parameters to shell of yachts length of: a –12 m; b – 24 m (s – thickness of shell, mm)

bearing in mind that the mass of floors decreases with decreasing spacing, and the cost of manufacturing – with its increase [12].

Reducing the deformations to values acceptable from the point of view of the appearance of the welded structure only through constructive measures is extremely difficult, so it is necessary to provide technological measures that eliminate the need to perform expensive camouflaging filler.

Firstly, according to the accepted technological sequence, one should initially weld the vertical seams of the joints of the beams of the frames between themselves and the adjacent horizontal sections of intermittent seams of the connection of the frames with the shell. Then, in compliance with the pitch and length of the welded section, intermittent seams are made in the remaining joints of the frames with the shell [13].

Secondly, local deformations of the shell of sections can be minimized by reducing heat input to the base metal, both by reducing the volume of the weld metal, but with guaranteed provision of the required weld thickness required by the Rules, and by reducing the degree of overheating of the metal being deposited [1–3].

An effective means of controlling the volume of the deposited metal and the degree of its overheating is welding with the use of impulse effects in systems of welding mechanized and automatic equipment [14–16]. Impulse effects ensure the achievement of two technological goals: 1) control of metal transfer and related processes and 2) control of the thermal cycle of welding and the formation of the weld.

To implement the technology of thin-sheet structures of yachts with controlled impulse effects, it is advisable to use combined systems that include a power source for pulsed arc welding and a specialized welding torch (Fig. 4) with a device for generating low-frequency mechanical vibrations of the electrode wire [11].

In-loop oscillations of the electrode wire are created using two solenoid-type electromagnets, the rods of which are handedly connected to the current-carrying tip. Electrode wire is fed to the welding zone through a flexible insulated metal tube. When alternately applying voltage from the control circuit to the coils of electromagnets, the electrode wire together with the tip performs transverse oscillations with a given frequency. The amplitude of oscillation is frames by adjusting the working stroke of the rods of electromagnets.

The oscillator is mounted on the nozzle of the torch with the ability to rotate 90 ° to ensure maximum access to the weld.

The advantage of the developed design of the torch with the in-nozzle oscillations of the electrode, compared with the existing oscillators of the welding tool (oscillators), is a significant, 40–120 times, decrease in the oscillating mass. As a result, a proportional increase in the maximum acceleration of the movement of the end of the electrode wire does not pose a danger to the reliability of the oscillator. This creates the acceleration required for the separation of the drop, and provides the ability to control the transfer of metal, heat input in the welded metal and the geometry of the seam. The disadvantage of the design is to increase the transverse size of the torch, which limits the ability to perform welding in areas adjacent to the intersection of the frames.

To select the working parameters of the transverse oscillations of the electrode, a diagram has been developed (Fig. 5), which also allows to predict some indicators of the automatic welding technology.

In the diagram, the numbers indicate three characteristic regions, within which the oscillations of the electrode wire lead to the following results:

1 – control of the weld seam is provided by changing the welding arc trajectory. Control of metal transfer is not possible.

2 – it is possible to combine control of the geometry of the weld and the type of metal transfer with the selected ratio between the oscillation frequency $f_к$ and amplitude $A_к$ for this diameter of electrode wire d_e;

3 – unstable arc burning and deterioration in the quality of weld formation due to excessively high speed of oscillating movement of the electrode wire.

It is obvious that the area of effective use of the torch with inner-nozzle oscillations of the electrode (WTINOE) is the area 2, in which at $f_o \geq f_{ctm}$, $d_e < A_o < e_0$ control of metal transfer and welding process productivity is provided;

at $f_o \leq f_{ctm}$, $e_0 < A_o$ – control of weld geometry without the need to change the welding arc oscillation trajectory.

In area 2 also, for comparison, the corresponding hatching also indicates the ranges of vibration mode parameters, which are implemented using known welding tool oscillators (WTO) and metal transfer control devices (MTCD) [17].

The technology of automatic welding using the torch WTINOE provides for the possibility of its installation on a self-movable welding carriage (Fig. 6).

Discussion of the results. The proposed method of designing standard sections of motor yachts made of aluminum alloys and the technological recommendations for the welding of a frames with plating allow to take

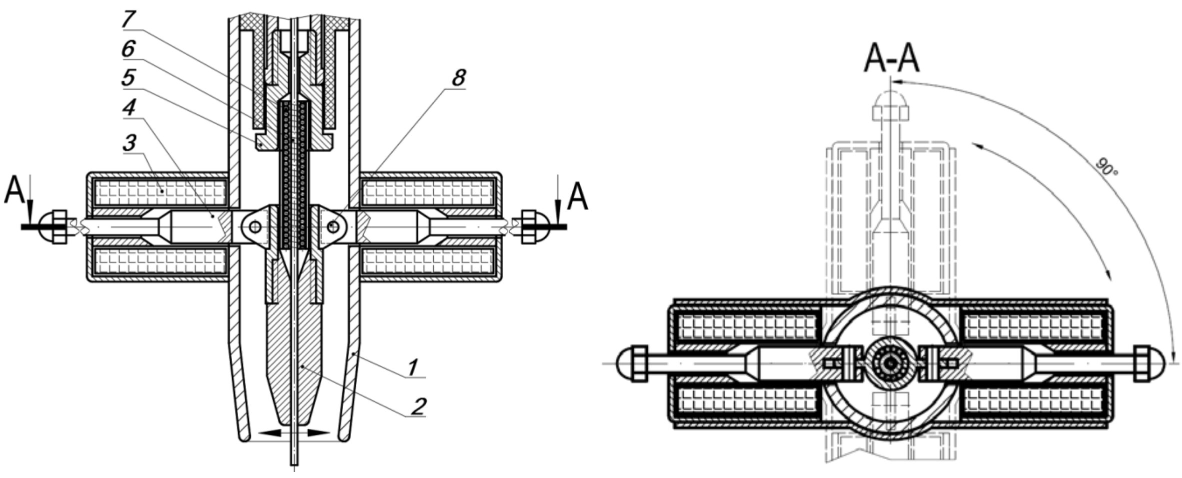


Fig. 4. The design of the torch for automatic welding in the environment of protective gases with intra-nozzle oscillations of the electrode wire: 1 – nozzle; 2 – tip; 3 – electromagnet; 4 – stock; 5 – insulating tube: 6 – electrode wire; 7 – spiral metal tube; 8 – hinge

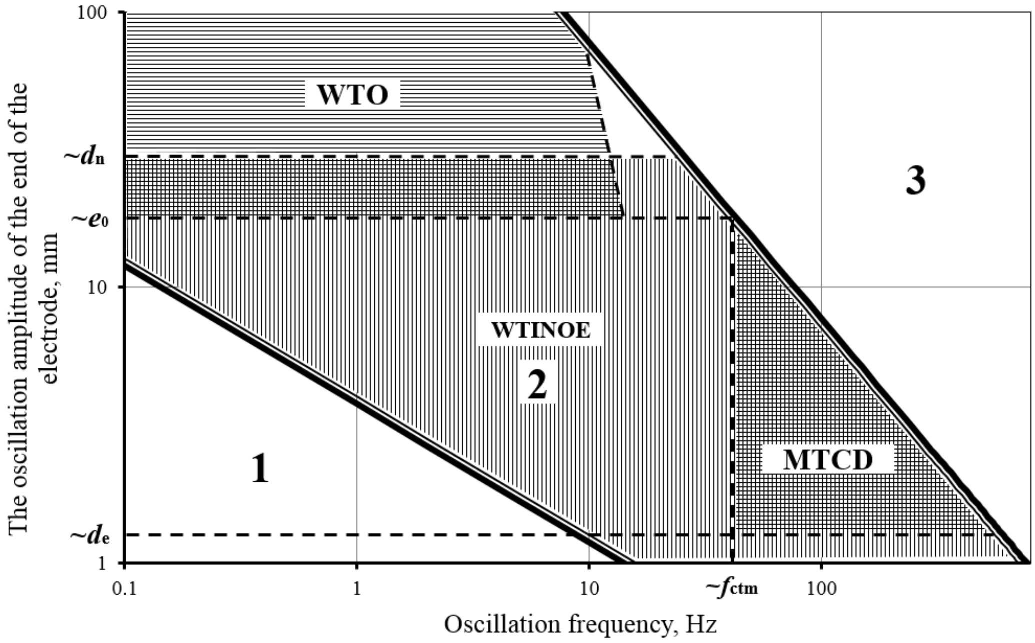
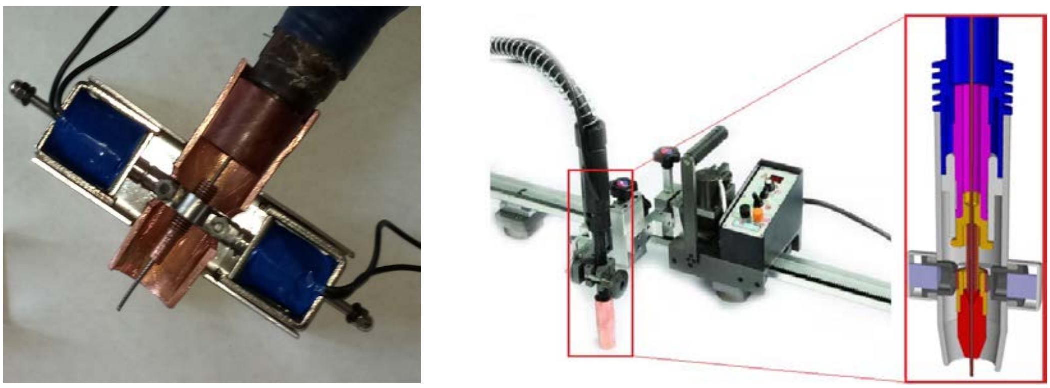


Fig. 5. Diagram for selecting the parameters of the mechanical oscillations of the electrode wire: e_0 – weld width without oscillation; d_n – nozzle internal diameter limiting maximum oscillation amplitude; f_{ctm} – minimum frequency of controlled electrode metal transfer



a b

Fig. 6. Appearance (with the half-nozzle removed) of the burner WTINOE (a) and the variant of its installation on the self-moving welding carriage (b)

into account the features of the construction of the structure. At the same time, the choice of plating thickness is made not only on the basis of the calculation according to the Rules, depending on the size of the spacing, but also taking into account the minimization of local deformations from the welding frames.

To implement the welding technology, it is necessary to preset the parameters of the oscillation mode of the electrode wire by selecting them using a nomogram (see Fig. 6) in area 1 or 2, depending on the technological purpose of the impulse effect. Straight-line sections of the weld (continuous or intermittent) are performed according to a predetermined cycle of the welding installation within the free access of the torch to the welding point. The peripheral areas of the connection at the intersection of the frames must be welded in a pre-mechanized way. This technology will provide an increase in the quality of welds, a reduction in the labor intensity of the section manufacturing and, in general, the cost of building a yacht.

CONCLUSIONS

1. To meet the increased requirements for the appearance of the hull structures of aluminum alloy yachts, the use of only constructive measures to reduce local deformations in the design is insufficient, which necessitates the implementation of costly post-welding editing and camouflaging works.

2. The developed method of designing typical hull structures of yachts, taking into account technological recommendations for minimizing local welding deformations of the shell of sections from welding the frames, allows you to select the optimal parameters of welds that meet the requirements of the Rules of Classification Societies, and ensures the implementation of mechanized and automatic welding technology.

3. To reduce the thermal energy introduced into the seam when welding a thin-sheet plating frames, a torch design with in-nozzle mechanical oscillations of the electrode wire was developed. The torch can be used in installations for automatic gas-shielded welding of ship structures made of aluminum alloys.

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