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New Technologies for Hull Assemblies in Shipbuilding

Nove tehnologije montaže brodskog trupa u brodogradnji

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Summary

The modern stage of shipbuilding industry development is characterized by an intense competition and the beginning of introduction of new materials and effective welding technologies, which change the appearance of this quite conservative field, at leading global shipbuilding enterprises. In particular, the application of laser technologies during ship construction decreases the cost of hull manufacturing by 30%, increases the production capacity by 10%, and reduces welding deformations by 30% compared to traditional welding methods. The application of composite materials for ship construction allows decreasing the ship weight by 10%, which leads to 1-7% decrease in fuel consumption, reduction of polluting emissions and significant saving of expenditures. Adhesion-bonded joints become more frequently used in shipbuilding, as they offer a possibility of joining different materials along with the advantages brought by the adhesion process itself, being reliable, cost-efficient and ensuring easy maintenance and repair.

KEY WORDS
fibre lasers
GMA welding
laser welding
assemblies in shipbuilding

Sažetak

Modernu fazu razvoja brodogradnje karakterizira intenzivno natjecanje i početak uvođenja novih materijala i učinkovitih tehnologija zavarivanja, koji mijenjaju izgled ovog prilično konzervativnog polja, kod vodećih svjetskih brodograđevnih poduzeća. Konkretno, primjena laserskih tehnologija tijekom gradnje broda smanjuje troškove izrade trupa za 30 %, povećava proizvodni kapacitet za 10 % i smanjuje deformacije zavarivanja za 30 %, u usporedbi s tradicionalnim metodama zavarivanja. Primjena kompozitnih materijala za izgradnju brodova omogućuje smanjenje težine broda za 10 %, što dovodi do smanjenja potrošnje goriva za 1 – 7 %, smanjenja zagađujućih emisija i značajne uštede troškova. Adhezijski spojevi sve se češće koriste u brodogradnji jer nude mogućnost spajanja različitih materijala uz prednosti koje donosi sam postupak prianjanja, jer su pouzdani, isplativi i osiguravaju lako održavanje i popravak.

KLJUČNE RIJEČI
vlaknasti laseri
GMA zavarivanje
lasersko zavarivanje
sklopovi u brodogradnji

1. INTRODUCTION / *Uvod*

Modern civilization is substantively nearshore. On a 200-kilometer strip along the coast of the World Ocean, half of the population lives, and more than half of all global industrial potential is concentrated. Maritime trade, industrial fishery, ocean research are the most important factors of the present time. Maritime activities and globalization are one of the main factors of stability of the whole world economy organism [1]. Maritime trade is the basis of the world economy. Around 90 percent of all the industrial products are transported with ships.

At present, global shipbuilding, especially the civil one, is going through quite a difficult period. The reason of this is quite an active production activity in the period preceding the world financial crisis of years 2008-2009. The lasting nature of this activity, shipbuilding field inertness, and economic recession, caused by the crisis, created a surplus of tonnage. In order to preserve and protect national producers, the governments of some countries, such as South Korea, Japan and China, provided them with a sufficient financial support. Various scenarios of crisis development and recovery, implemented by various countries, strengthened the trend of shifting the centre of global shipbuilding to the Far East. During the financial crisis, the distribution among the shares of shipbuilders from the East and Europe increased due to low expenditures on labour costs and production on Asian shipyards [2].

It is worth mentioning that during the first half of the 20th century the main role in global shipbuilding belonged to the countries of Western Europe. But already at the beginning of 1970s Japan took first place in the overall total of shipbuilding. By the end of 1970s, South Korea has also become one of the main players in this field; and when China entered this market in 1990s, the transition of the global shipbuilding centre to the East became inevitable, and the competition on the shipbuilding market increased significantly.

According to the data [3], at the end of 2017, the leader of the global shipbuilding is undoubtedly China (39%), followed by South Korea (25%) and Japan (21%) (Fig. 1). For the operation of all marine installations and types of watercraft, including oil-tank ships, LNG carriers, cruise ships and bulk carriers, one of the main tasks is theincrease of a fault-free operation time, production increase and vessel weight decrease.

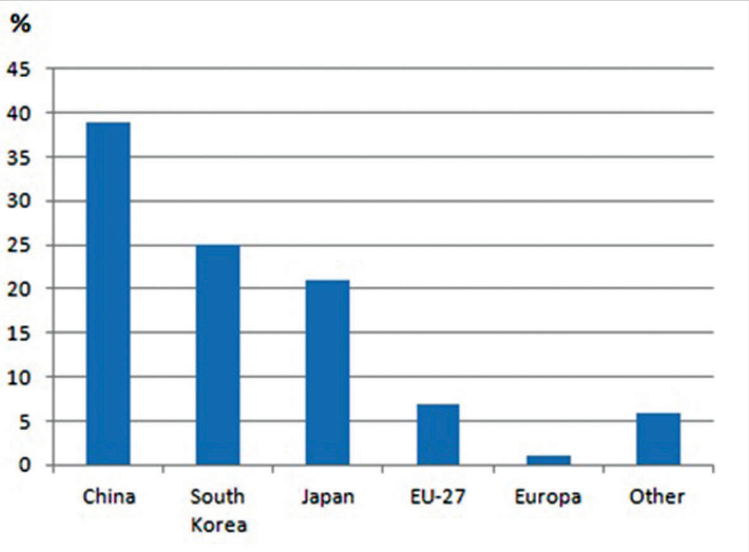


Figure 1 Structure of the shipbuilding orders portfolio by countries, 2017 [3]
Slika 1. Struktura portfelja narudžbi za brodogradnju po zemljama, 2017. [3]

It should be mentioned that structural engineers and designers have been intensively working on the issue of vessel weight decrease since the origination of shipbuilding and up until now. The introduction of electric welding played a crucial role in this. Due to its application, the ship hull weight decreased by 15-20%, even to 30% in some cases. Welding is one of the main technological processes without which it would be impossible to imagine a vision of shipbuilding [4]. Namely, the modern stage of the development of machine building field and shipbuilding is characterized by the beginning of introduction of the technologies, which are drastically changing the image of this quite conservative field, at the leading world shipbuilding enterprises. These changes are caused by the increasing requirements to performance capability and reliability of products, while preserving and decreasing their competitive cost [5, 6].

Modern ships consist of thousands of subcomponents and structural elements of the hull and furnishing. The total length of structural joints can constitute approximately 400 km in a big cruise ship. Besides, a lot of welding works are done for the connection of technical devices, different finishing materials and equipment, in order to receive high-quality joints in vessel final assembly and fitting-out.

The weight of the metal applied during welding process can constitute from 3 to 4% of the total weight of ship metal, and its value is almost 10 times higher than the value of the same weight of ordinary metal [7]. Connecting operations constitute approximately 50% of the total amount of production hours and cost of ship construction, both due to direct expenditures and potential execution of additional works caused by thermal deformations. In some cases, these non-productive operations can constitute up to 30% of total works in the hull manufacturing. Besides, during the execution of erection works aboard the ship, a high temperature of welding arc usually conflicts with equipping operations and can cause the damage of previously installed components. Therefore, accuracy and efficacy of connecting processes are key consequences for the competitiveness of a shipyard.

At the moment, the following kinds of welding are used for making connections at shipyards: Shielded Metal Arc Welding (SMAW), Submerged Arc Welding (SAW), Metal Active Gas Welding (MAG), Metal Inert Gas Welding (MIG), Gas Tungsten Arc Welding (GTAW), Flux Core Arc Welding (FCAW). At that, submerged arc welding (SAW) constitutes approximately 15% [8 - 11].

The mentioned kinds of welding are characterized by significant thermal deformations. The deformations created in the process of welding are closely connected with residual stresses and, in many researchers' opinion, they are an inevitable problem during welding [12, 13]. These authors also state that welding deformations not only deteriorate the aesthetic aspect, but also pose a threat to the structural integrity of the vessel and can lead to its destruction. Process operations for details adjustment and correction of finished structures can take up to 30% of the total time of ship hull manufacturing, if traditional welding methods are used [14].

Besides, quality and reliability of welded structures are significantly influenced by the efficiency of execution of process operations preceding the welding process, such as cutting, preparation of welding surfaces, and assembly of workpieces. The elimination of deficiencies resulting from the execution of the mentioned operations later requires quite a lot of material expenses and time, and in the majority of cases it is practically impossible to correct the mistakes which have been made.

Taking into consideration the fact that welding works on a ship or a shipbuilding yard are usually carried out under extremely severe conditions, the operation characteristics and handiness of the used equipment and technologies must correspond to the highest requirements.

That is why, as of today, of relevance are the issues of an improvement of quality and finished product reliability, avoidance of additional operations due to the problem with proper preparation of workpieces to welding, and thermal deformations, as well as mechanization and automation of production processes in relation to difficult working conditions on shipbuilding yards and ship repair facilities.

2. LASER PROCESSING OF DETAILS / *Laserska obrada detalja*

At present, none of strategically important technology directions in the world do without using lasers during material processing. Laser technologies to a big extent determine the development of virtually all the fields of the modern industry and are actively used in machine building, motor vehicle industry, nuclear, space, aircraft and shipbuilding industries. Shipbuilding industry became one of the first industry fields to show interest in technological lasers [15, 16]. At the same time, it was noticed that the introduction of laser technologies in shipbuilding goes on in a quite slow pace [7].

The appropriateness of laser processing application and its advantages are defined by the possibility of a quick, strictly dosed, intensive energy supply to the product surface. The ways of laser treatment are contactless and enable to treat hardly accessible and local areas of the details without any vibrations and other negative impacts on the material. There is ensured localness in depth and area of physical processes happening in the heat-affected zone, while original material properties are preserved in another volume, and there are no significant deformations of processed parts.The combination of the above mentioned properties of this way of thermal treatment makes it possible to increase the operation reliability and working life.

Cutting is one of the most responsible operations in shipbuilding, and laser application in this field has been increasing for many years. On shipbuilding yards, the use of laser cutting machines started in 1995. Their application was mainly caused by the need of cutting thick plates. These were CO2 laser systems, and their power constituted 6 kW [17].

At first, it was considered that laser cutting would be hard to apply in the shipbuilding industry due to various and complicated requirements to chamfer preparation. In many cases, plasma-cutting machines and mechanical machines are typically used here.This situation changed due to the development of different process cutting operations executed with a laser torch. On shipbuilding yards, it was proved that laser cutting can achieve a high precision and can reduce time and expenditures on post-cutting processes, like assembly works and welding [9].

Laser cutting has a number of significant advantages compared to plasma or oxy-fuel cutting (table 3). First of all, this is a high accuracy of detail cutting while thermal deformations are virtually absent, which is provided due to the minimal cutting width, the absence of scarfed edges, and minimal gas-dust emissions that are easily removed by means of a local low-power exhaust.In case of using 3-4 kW power lasers incorporated in the machines, it is possible to get precision cutting of the details having width up to 20 mm. Therewith, the increase of expenditures on detail cutting is regained by way of exclusion of adjustment works during the assembly of vessel hull structures.

Laser cutting is a key and a decisive kind of laser treatment which allows to drastically upgrade the technology of assembly and welding works in shipbuilding manufacturing and to significantly improve the accuracy of workpiece manufacturing and, correspondingly, to reduce the amount of deposit metal during welding works, which, in turn, gives a 5-10 times decrease of the labour intensity of welding, and then adjusting, works for deformation correction.This, in turn, gives a 10-30% decrease in the construction time, as well as in the steel structure weight, the specific amount of metal, due to an increase of stiffening rib pitch or a decrease of the used metal thickness. Laser cutting allows reaching the accuracy of 0.2-0.4 mm on the length up to 10 m, with the cutting width of 0.5-0.8 mm. The defects on the surface of the cut edges, including also the size of the weld burr, do not exceed 0.1-0.3 mm. So, the accuracy of workpiece manufacturing and the size of processing defects are measured as tenths of a millimeter in the case of laser welding, while with traditional techniques the scattering of dimensions and defects of edges reach one millimeter and more [19].

It is more correct to call laser cutting a mechanical treatment. Using 5% laser source power, marking of hull parts was made, with the indication of their sequence numbers, zero points, lines of frame installation and flanging.In addition to profile cutting, high precision and small cutting width also allow to use this process for the cutting of all round holes having up to 3 mm diameter instead of drilling and punching them.

During the assessment of the benefits of a new material treatment process, high quality characteristics of laser cutting should be taken into account, in addition to strictly economic values. The absence of deformation and burrs eliminates the need for additional operations of mechanical treatment of edges and correction of workpieces after cutting, and makes it possible to manufacture details with final dimensions for assembly and to severely reduce detail manufacturing time, which is especially important if urgent supply of products is necessary. As a result, quality considerations will complement and strengthen strictly economic values.

Laser shaping became a viable process of metal components forming as a means of quick prototyping, adjustment and alignment. This process is analogical to the process of bending with the help of the flame, which is used on a big sheet material in shipbuilding industry, but in this case a more accurate control over the final product can be achieved. The paper [20] describes the mechanisms of laser shaping and considers the potential that the process has for shipbuilding industry. Authors reported experimental results of a high level of 2D and 3D laser shaping of material with thick cross-section. The results show the potential of the process for the shipbuilding from the

Table 1 Comparative characteristics of different kinds of cutting [18]
Tablica 1. Usporedba značajki različitih vrsta rezanja [18]

Technology	Units	Laser cutting	Plasma cutting	Oxy-fuel cutting
Cutting width	mm	0.5 - 0.8	2 – 3	3 - 10
Cutting speed	m/min	3-8	5	1.0
Heat affected zone width	mm	0.3-0.5	1-2	5
Roughness	µm	10- 80	300	500
Taper	degrees	Less than 1°	3° - 10°	absent

point of view of obtaining necessary shapes and the process of secondary deformations correction.

3. LASER WELDING / *Lasersko zavarivanje*

According to the analysis of world leading producers, the manufacturing quality is the key factor of reaching the productivity. Technological operations for details adjustment and correction of finished structures can take up to 30% of the total vessel hull manufacturing time, if traditional welding methods are used [14]. The application of deformation-free laser technologies is the way to increase productivity and to improve quality of the finished product.

Laser welding is the process during which heating up and melting of workpieces to be joined are carried out with a coherent beam of monochromatic light. Due to a high concentration of energy and a small heated spot, the volume of a weld pool during laser welding is a few times smaller than in the case of arc welding. This factor influences a set of characteristics of both weld seam and product in a positive way. First of all, a 2...5 times decrease of seam width allows to expand the range of details where the area for seam execution is limited both from the point of view of thermal effect and compact size [21]. Besides, the decrease of melt volume and the obtainment of seams with a big ratio of penetration depth to seam width enables to get the detail deformation decrease of up to 10 times, while a small volume of melted metal and a specific shape of the seam also improve metal crystallization conditions in a number of instances [22].

Laser welding has been used in shipbuilding for a long time. In particular, the article [59], which was published in 2005, indicated some European shipbuilding companies that used this technology: Meyer Werft of Papenburg, Germany; Blohm+Voss, Hamburg, Germany; Odense Steel Shipyard (OSS) near Odense, Denmark; Fincantieri, Monfalcone, Italy; Aker Kvaerner Masa yard in Helsinki, Finland; Aker Warnow Werft near Rostock, Germany, and others. Currently, these technologies are used worldwide for various classes of ships.

During deep-penetration welding, the melt bath has a peculiar shape, elongated in the direction of energy source movement (Fig. 2). In the front part of the bath there is a channel or a crater filled with metal vapor.

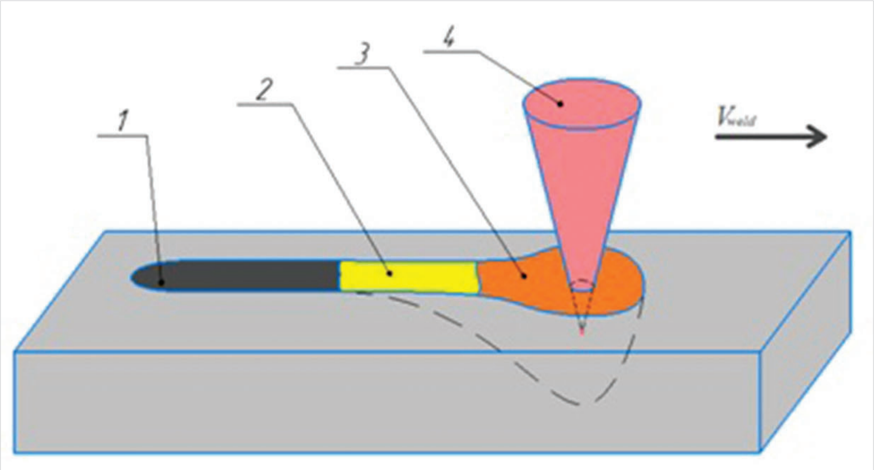
On the front wall of the channel there is a layer of a molten metal. In which case, a peculiar step-shaped bend of a front wall is observed which occasionally moves along the channel height. Along the side walls of the channel, a transfer of molten metal from the front part to the tail part happens in a horizontal way. The molten metal of a tail part of the bath goes up in whirling flows to the melt bath surface. Above the melt bath surface, a bright plasma flame is observed in the process of laser welding [23].

The seam formation and mechanical properties of a welded joint are influenced by the processes of mass transfer of the molten metal in the melt bath.

At an appropriate speed of a laser beam movement, the created cavity acquires dynamical stability and moves together with it. Before the cavity, the melting of material happens; after it, there is solidification. If the cavity is present, the emission is absorbed not only on the material surface but also in its depth. After the beam passes, the cavity is filled with molten metal, a narrow seam is created, and its depth is significantly bigger than its width. The depth of melt penetration at a set level of laser emission power is inversely related to the speed of welding. The highest speed is limited by the value at which metal crystallizes, having not enough time to flow over the welding edges, with the formation of shrinkage porosity. The bottom speed limit is limited by the value, at which, due to heat conductivity, the metal melts to sides quicker than deep in, accompanied with a significant increase of seam width and heat-affected zone, as well as with the grain growth in the seam metal. Optimal steel welding modes are ensured at relatively high speeds (up to 1.5 ... 2 m/min). At that, the laser emission power can be previously selected under the condition of 1 kW per 1 mm thickness of the detail that is being welded.

A harsh thermal cycle of laser welding with high speeds of heating up and cooling down ensures a significant process strength and plasticity of welded joints, gives a possibility to considerably decrease the heat-affected zone, allows to reduce the effect of phase and structural transformations in the area around the seam [24].

Since the introduction of laser technologies, in the majority of cases CO_2- lasers have been used, the power of which reached tens of kilowatts. A shortcoming of gas lasers is their small coefficient of



1 – Weld joint; 2 – Melt bath; 3 – Keyhole; 4 – Laser beam
1 – zavareni spoj 2 – metalna kupka 3 – ključanica 4 – laserska zraka

Figure 2 Schematic view of laser welding process
Slika 2. Shematski prikaz postupka laserskog zavarivanja

Table 2 Speed of welding for different methods [7]

Tablica 2. Brzina zavarivanja za različite metode [7]

Plate thickness	Units	4 mm	6 mm	8 mm	12 mm
MIG / MAG	mm/sec	1.1	0.9	0.75	0.55
Plasma	mm/sec	0.45	0.35	0.25	-
Laser	mm/sec	20	15	1.2	1.2

efficiency: for example, for a laser of 5 kW power ensuring welding of steels of 5 mm thickness, consumed power constitutes 100 kW [25].

After fibre lasers having the power up to tens of kilowatts appeared on the market, significant changes started to happen in this market segment [4]. This is related to the fact that achieved power parameters allow to weld materials of up to 20-30 mm thickness. Due to a high coefficient of efficiency, energy consumption significantly decreased, maintenance of systems became simpler, parameters of weight and dimensions dropped. An innovative element that has created the preconditions of the emergence of such structure is a fibre-optic cable [26]. Experiments proved that in case of welding steels with powers up to 5000 W, the production process can be successfully carried out within a long time period, and welded joints of good quality can be obtained.

The main indicator of expenditures and efficiency of hull assembly process is the speed of welding [7]. Table 2 reports comparative values of speed for different welding techniques. Based on the mentioned data it follows that the use of laser welding significantly increases the speed and production capacity of manufacturing processes during vessel hull assembly.

Laser welding with fibre lasers quickly becomes a very effective connection in shipbuilding where it saves time and manufacturing expenses compared to usual processes of arc-based welding [27]. An increasing use of laser technology expresses itself in the sales statistics showing annual growth paces of more than 10% in the last several years [28, 29]. Modern fibre-optic lasers do not require complicated maintenance, are easily integrated with industrial robots and produce weld seams with deep penetration at a high throughput capability [30, 31]. The high quality of beam at high levels of power and the decrease of price per kilowatt of laser power allow to overcome previous limitations and to open new possibilities, especially in welding of lock keyways.

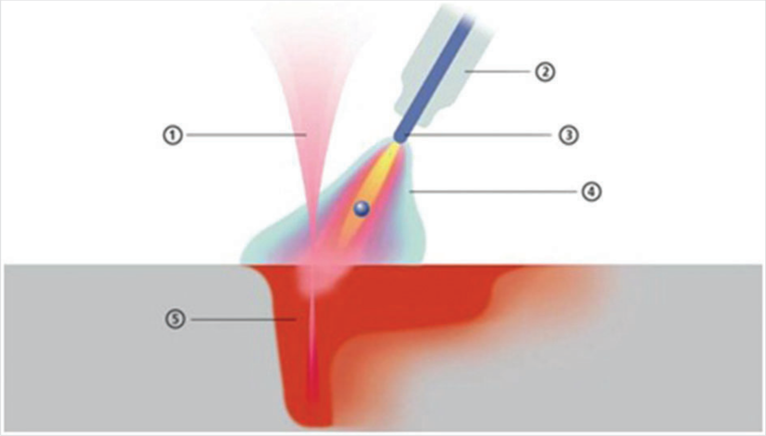
The main limiting factor preventing a wider use of laser welding is its exceptional sensitivity to accurate positioning and high demands to the mechanical treatment of welding surfaces [32]. In case of laser welding, an allowable gap between the edges constitutes up to 0.2 mm. Big gaps result in such defects as seam droop or lack of fusion [33].

One of effective ways to compensate for the variation of interruptions and to ensure execution of weld seams of an acceptable quality is the application of hybrid laser-arc welding [34]. In hybrid welding, two welding processes are combined which are acting simultaneously in the same area: the arc heats up the metal and complements the effect of laser emission (Fig. 3). That is why hybrid laser-arc welding needs lasers of less power compared to laser welding, and this makes the process cheaper. In this regard, welding speed and penetration depth are considerably higher than the corresponding values of each of these processes individually. For welding, filler material is also used.

Laser-arc welding has significant process advantages and allows to control the weld shaping by way of adjusting arc parameters; also, it expands gap throughput [36]. In laser-hybrid process, an expensive laser energy is solely used for the deep penetration effect, which also allows to weld thicker plates. The rest of the energy is provided by a cheaper MIG/MAG process, which guarantees a better clearance bridging due to the use of the electrode that melts. The advantages of laser-arc welding encompass deep penetration, low level of residual deformations and the decrease of demands to abutting of edges to be welded.

Due to welded metal heating up with an electric arc, a laser emission coefficient increases leading to a reduction of laser energy losses and an increase of welding speed. The same effect shows itself in the increase of a cross-section area of metal melted during hybrid welding compared to the sum of cross-section areas of beads received by way of separate arc and laser welding [37].

Metal, increases the penetration depth and welding speed [36]. All of this leads to heat supply decrease, makes it possible to execute single-sided welding as one-pass welding and when the positioning of workpieces is inaccurate. Single-sided weld joints are the easiest in execution and the least labour-consuming [38]. The modification of a thermal cycle of laser welding, which happens under arc effect, improves the structure of weld seams [39].



1 - laser beam; 2 - gas nozzle; 3 – electrode; 4 - pulsed welding arc; 5 - melt-through

1 – laserska zraka 2 – mlaznica za plin 3 – elektroda 4 – pulsni luk za zavarivanje 5 – protapanje

Figure 3 Laser-hybrid welding process [35]

Slika 3. Postupak lasersko-hibridnog zavarivanja [35]

In case of combination of laser welding with an electric arc, the arc improves the quality of seam filling. Therefore, laser-hybrid welding demonstrates better seam properties, higher welding speeds, less deformations and a lot of other things, decreasing the cost of additives. At the same time, there is a decrease in polluting gas emissions and UV radiation that covers high ecological standards and creates a safer and more comfortable working environment [37]. The comparison of calculated thermal cycles shows that hybrid laser-arc welding ensures better conditions for weld shaping, heat-up regulation and melt adding than laser welding.

The paper [40] compares laser-hybrid welding with other technologies (Table 3). The reported results were obtained with the use of a carbon dioxide laser of Trumpf Laser technology company and Fronius TPS 5000 microprocessor power source. Table 3 shows the welding speed for different technologies according to the cited literature in comparison. Obviously, the welding speed is very different for different equipment and depends on the thickness of the metal being welded. In this case, the welding speed for laser-hybrid welding technology reaches 3 m / min according to the information [9]. For fatigue tests, the data in Table 3 are confirmed by other sources. In particular, according to the information [9], 20 mm thick metal samples withstood 10^6 loading cycles with maximum stresses of 420 MPa.

The investigations were conducted for butt joints of the material of up to 15 mm thickness. The submerged-arc welding technology ensures 2 to 5 mm clearance bridging at up to 12 mm material thickness. In case of using laser hybrid technology, it is possible to reach up to 1 mm clearance-bridging ability in case of up to 15 mm material thickness, but at the same time the speed of welding is 3 times higher than the speed of submerged-arc welding and 2 times higher than laser wire welding. The application of laser wire welding technology allows reaching up to 0.4 mm clearance-bridging ability at material thickness up to 15 mm. In order to assess the maximum welding speed at a maximum clearance value, materials having the thickness of 5, 8, 12 and 15 mm were used. The influence of helium and argon shielding gases on the hybrid welding technology was investigated by means of standard methods. For welding with highly powerful carbon dioxide lasers, a helium fraction of shielding gas is mainly needed.

Hybrid laser welding minimizes the shortcomings of both laser and MIG welding. In order to achieve the advantages of hybrid laser welding, a proper selection of process parameters is needed.

In spite of clear benefits of laser-arc welding, this process is still at the initial stage of introduction to present-day fields of industry. The reasons of a slow pace of industrial implementation are a high investment cost and the complexity of the process related to a big amount of its parameters [41]. At the same time, hybrid welding has already gotten some spread in such industrial fields as motor vehicle industry, shipbuilding, pipeline transport, aerospace and aircraft industry, energy production.

4. WELDING OF SANDWICH PANELS / *Zavarivanje sendvič-panela*

Peculiar for shipbuilding industry is the use of sandwich panels reducing vessel structure weight, ensuring lower fuel consumption, higher speed and maneuvering ability of ships [42, 43]. The analysis of modern vessel hulls shows that flat panels are widely used in the structures of platform, board, bottom, partition. These panels constitute 70-75% and 85-90% of a vessel hull, respectively [16, 44].

Some of the main defects in thin panel structures are the residual stresses causing significant bending. At the same time, such problems can be solved with the help of laser welding.

The manufacturing of laser-welded metal sandwich panels at Meyer Werft showed the potential of laser welding for the creation of completely new structures. The application of laser welding technologies showed that in case of manufacturing panels with the length of weld seams up to 16 m the productivity increases by 100% due to a significant increase of welding speed, as well as low heat input, and, as a result, an exclusion of further manual treatment, for example, correction. The comparison of gas-shielded arc welding to laser welding shows that in case of the latter it is possible either to decrease the panel thickness, or to increase the distance between the stiffening elements without any loss of stability. At that, apart from a weight decrease, the execution of heat-insulation and soundproofing measures becomes simpler. Indeed, for the installation of wiring system, the space between the top and bottom sides of the panels is used. One of the examples of applying laser technologies in shipbuilding is Norwegian Dawn cruise liner, during the manufacturing of which 900 km of seams were made, and 480 km out of them were executed by means of laser-arc welding [44].

PEMA company together with Lincoln Electric developed high-efficiency welding processes for single-sided butt welding by means of laser-hybrid welding with the thickness of 4 to 25 mm for high-strength steel. A nominal working cycle for normal thin panels of 20 ... 25 m length on the inside constitutes approximately 30 minutes. Stiffening ribs can be welded by means of laser-hybrid welding or MAG process. At that, the speed of laser-hybrid welding constitutes 2-3 meters per minute, while for MAG welding it is 1.5-2 meters per minute [45].

Quite promising are also production upgrade projects of MV Werft company in Rostock, where the most advanced in the European Union laser-hybrid welding machines are located. With the help of automated processes, they manufacture big

Table 3 Comparative characteristics of different kinds of welding [40]
Tablica 3. Usporedba značajki različitih vrsta zavarivanja [40]

Technology	Units	Submerged-arc welding	Laser-hybrid welding	Laser welding
Speed of welding	%	100	300	150
Thickness	mm	< 12 mm	< 15 mm	< 15 mm
Gap	mm	2 – 5 mm	0 – 1 mm	0 – 0.4 mm
Deformation	mm	< 1.5 mm/m	< 0.2 mm/m	< 0.1 mm/m
Fatigue characteristics		Good	Excellent	Critical

steel panels of up to 400 square meter (25 x 16 m) size on such machines. The single-sided butt welding station with a laser-hybrid welding head is complemented with automated profile assembly featuring double-sided welding of profiles by means of a laser-hybrid process. For a shipbuilding yard, an automated welding line for thin panels is a part of a wide digitizing concept, which sets 4.0 industry processes in shipbuilding [46].

Laser-hybrid technologies were also used for the upgrade of STX shipbuilding yard in France, which constructed the biggest cruise liner of its time, Harmony of the Seas, in 2016. The 362-meter-long and 66-meter-wide behemoth can carry 6,360 passengers and 2,100 crew members [46].

It is worth remarking that preparatory operations, namely the positioning of the weld surface ends, requires considerable investments in large-scale machinery and equipment, which can only be afforded by certain shipbuilders constructing big passenger vessels. However, for the shipbuilders constructing general commercial vessels, Mitsubishi Heavy Industries, Ltd. (MHI) company has developed a mobile set of equipment. The technology of Mitsubishi Heavy Industries, Ltd., expects the application of laser cutting for the preparation of welding surfaces, and the fixation of surfaces before welding is done by way of tack welding with temporary weld spots instead of large-scale clamping equipment securing the whole area of a welded steel sheet. These weld spots are made with the use of arc technique. During the execution of the principal weld using laser-arc welding, the preliminarily created spots get melted together with the base metal and create a weld seam of a good quality.In such a way, it confirmed the possibility of obtaining the weld seam, that corresponds to the regulatory documents, without the application of large-scale clamping equipment [41].

Sandwich panels have considerable advantages compared to typical orthotropic plate-like structures, such as high strength and rigidity, improved fire safety and heat insulation, corrosion resistance, as well as high accuracy, modular structure and ease of assembly. In some areas of application, the structural weight of the structure can decrease by 50%, if sandwich panels are used [16].

Based on the investigations conducted in the recent years, a conclusion can be made that laser-arc hybrid welding ensures better conditions for seam formation, heating adjustment and filler material addition than laser welding or arc welding separately [9].

Due to the use of thin panels in the up-to-date designs of vessels, it is easier to increase their speed and agility, decrease the weight and ensure better fuel saving. The reduction of plate thickness is a challenge not only for shipbuilding but also for computer-aided manufacturing [47].

Of note is also the fact that the widespread introduction of sandwich panels to the vessel design changes the specific nature of shipbuilding. Instead of steel structure manufacturing, more and more mounting works related to the assembly of special panels, manufactured in highly-specialized production, are carried out at shipbuilding yards [42, 44].

5. LASER WELDING IN VARIOUS SPATIAL POSITIONS / *Lasersko zavarivanje u različitim prostornim položajima*

While it is possible to use simple kinematic schemes for the execution of straight welds during the preliminary assembly of structures, systems with a more controlled axis are needed for implementing complex geometry structures of three-dimensional and upright horizontal welds, for example, on the crossing points of profiles and beams. Due to a flexible beam pointing, solid-state laser fibre-optic systems are suitable for effective integration into robotized machines [48].

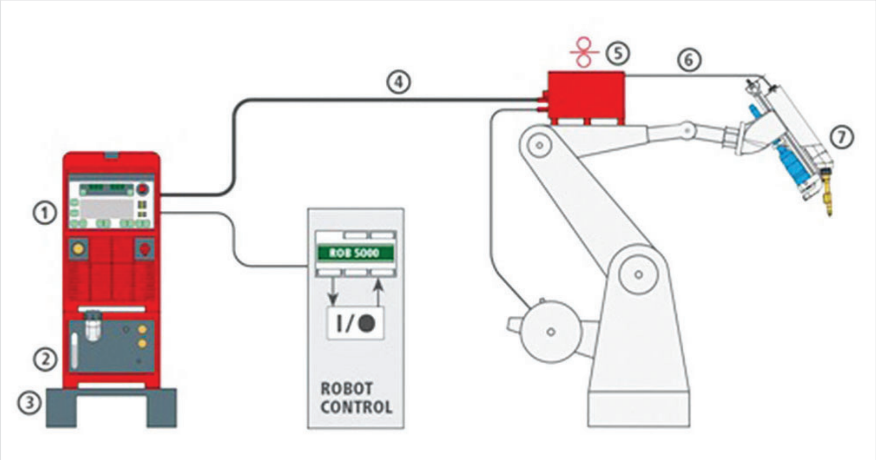
The authors [9] developed a robotized equipment complex for laser cutting and welding of structures in various spatial positions intended for the manufacturing of complex geometry structures.The complex is based on a modular system and performs laser and hybrid laser-arc welding of steel structures of up to 20 mm thickness and aluminum alloys of up to 12 mm thickness. The machine is unique due to the use of 25 kW laser LS-25, as well as an optical 4-channel switch, which, in turn, allows using laser optical heads for welding and cutting with the same machine, and this significantly shortens the time of welded structure manufacturing. The application of such set of equipment in shipbuilding decreases the cost of hull manufacturing by 30%, increases the production capacity by 10%, and reduces welding deformations by 30% compared to conventional welding methods.

Quite promising for the use in shipbuilding is the laser-hybrid technology of Fronius company (Fig. 4). This technology ensures optimal clearance bridging and easy preparation of a weld seam, which are peculiar for MIG process, as well as low thermal influence, deep penetration and laser welding speed. Due to this, it is possible to connect different steel and aluminum details with the speed of up to 8 meters per minute and the highest quality.

The basis of a laser-hybrid welding system is a compact laser-hybrid head with integrated MIG/MAG welding gun and laser optics [35]. A robot holder connects a laser-hybrid head with a standard industrial robotized system. This provides the head with the necessary flexibility for working on poorly accessible areas of the detail. Welding wire can be placed in any position relative to the laser beam, which allows to accurately adapt the process to the most diverse ways of weld seam preparation, results, types and classes of wire, as well as welding tasks.

It is worth mentioning that during the welding of large steel structures the biggest problem consists in the discrepancies of geometrical dimensions caused by inaccuracy at previous manufacturing phases.These discrepancies of geometrical dimensions and shapes resulting from the manufacturing of details and subcomponents are the utmost factors that often block and slow down effective robot-aided welding [49].

The problem is that discrepancies cause the fluctuation of the weld groove cross-section and position. In other words, the developed structure and prefabricated welded structure have big geometrical deviations, which it is not always possible to eliminate with the help of common methods.



1 - TransPulsSynergic; 2 - cooling module; 3 - vertical console; 4 - connecting hose package; 5 - wire feeder for robotized system; 6 - hose package of a welding gun; 7 - laser-hybrid welding head

1 – TransPulsSynergic; 2 – modul za hlađenje; 3 – vertikalna konzola; 4 – priključni paket crijeva; 5 – dodavač žice za robotizirani sustav; 6 – paket crijeva pištolja za zavarivanje; 7 – lasersko-hibridna glava za zavarivanje

Figure 4 Laser-hybrid system [35]

Slika 4. Lasersko-hibridni sustav [35]

Now PEMA WeldControl 300 SCAN has surpassed this challenge. The system scans the real geometry of the groove and, correspondingly, provides the welding robot with its outlines. The software takes into account the actually received information and in such a way the processed detail and its positions will correspond to reality, which allows to clarify the necessary amount of welding materials and welding process parameters [50].

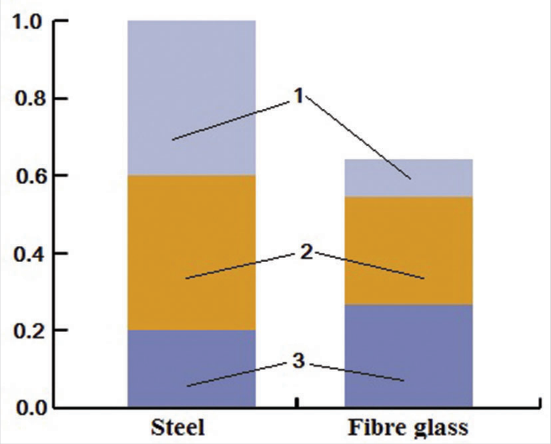
6. ADHESION-BONDED JOINTS / *Adhezijski spojevi*

It is known that aluminum alloys and composite materials are usually used in the upper structures of passenger and high-speed vessels, while smaller vessels can be completely made of lightweight materials. The aim of lightweight materials use is a decrease of vessel weight and an increase of production efficiency [51].

Quite promising is the manufacturing of vessel pipeline systems from glass fibre. Showing excellent corrosion characteristics, fibre-glass pipelines extend the operation life of the off-shore facilities [52]. Usually steel pipeline systems must be replaced 2-3 times within the whole operation life of the off-shore facility, while fibre-glass ones endure the complete designed lifetime, reducing the overall cost of the facility (Fig. 5). Glass-fibre pipeline systems are also ecologically friendly and do not constitute any threat for the environment [53]. Joining of glass-fibre pipes is done by way of adhesion bonding. Adhesion-bonded joints become more frequently used in shipbuilding, as they also offer a possibility of joining different materials along with the advantages brought by the adhesion process itself, being cost-efficient and ensuring easy maintenance and repair.

The combination of steels and composite materials in the structures to be adhesion-bonded can decrease the weight while preserving the strength, which will result in the manufacturing of lighter and stronger vessels. It is known that 10% decrease of vessel weight leads to 7% decrease of fuel consumption. Potential savings along with production advantages are the motivation for a widespread use of adhesion-bonded joints in various structures of the shipbuilding industry that are able to resist high loads and guarantee ship safety [54].

Adhesion-bonded joints and light materials at present came into common use in the field of space industry and motor vehicle industry but their acceptance in the shipbuilding industry, especially what concerns the manufacturers of large vessels like cargo vessels or sea ships, still falls behind. Production processes in airspace and motor vehicle industry are often carried out under controlled conditions, where dust and waste are rare and the temperature is adjusted, while shipbuilding operations are often exposed to open air, which complicates the severe control of the process needed for effective bonding with an adhesive. This complexity facilitates the general problems regarding reliability and fatigue duration of the adhesive substance exposed to the influence of harsh marine environment during its operation life.



1 – Maintenance & repair; 2 - Prefabrication & installation; 3 – Materials

1 – održavanje i popravak; 2 – prefabrikacija i ugradnja; 3 – materijali

Figure 5 Comparison of operation expenditures for fibre-glass and metal pipes [52]

Slika 5. Usporedba operativnih troškova za stakloplastične i metalne cijevi [52]

The use of an adhesion-bonded joint enables to effectively replace welding in some cases, to reduce deformations, to eliminate residual stresses and to improve fatigue characteristics compared to welded joints [55]. The main function of an adhesive is the transfer of loads from one surface to another one. Avoidance of processing at high temperatures allows using safe construction practices in harsh conditions. Adhesion bonding of composites provides with a well-distributed load and maximizes the use of adherent materials.

At present, shipbuilding mainly uses polyether, polystyrol and epoxy kinds of adhesives, which are also used in other industrial programs [56]. Adhesive bonding is a complex process with many variables. At present, there are no techniques of nondestructive testing for an adhesion-bonded joint to determine the adhesive strength of a completed joint in a reliable manner. Thus, it is necessary to establish a quality control system for each joint as an individual stage of the manufacturing process in order to ensure the reliability of joints. Nondestructive testing techniques can play an important role in quality assurance of the production processes.

The authors [57, 58] conducted investigations of adhesion-bonded joint durability for steel and aluminum. As a result of research, it has been found out that the application of coating, i.e. base coating, before adhesion bonding positively influences the strength of the joint. As an alternative, adhesive can also be applied directly on bare metal, but then the joint needs to be protected from aggressive environment.

At present, limited production experience with the duration of adhesive action can be compensated for by the reliability of joints. In case of joining important components, a solution can be chosen where mechanical fastenings are used in combination with an adhesive. It is worth mentioning that such way of connection can have a good outlook in shipbuilding.

Therefore, a conclusion can be made that the efficiency of using new construction materials depends to a significant extent on the availability of corresponding joining technologies. That is why, it is still necessary to conduct experimental, analytical investigations, to study production experience, in order to obtain the knowledge about the long-term efficiency of adhesive use for shipbuilding and their operation in the aggressive marine environment.

7. CONCLUSIONS / *Zaključci*

The modern stage of shipbuilding industry development is characterized by an intense competition and the beginning of introduction of new materials and effective welding technologies, which change the appearance of this quite conservative field, at leading global shipbuilding enterprises.

Conventional kinds of welding used in shipbuilding: Shielded Metal Arc Welding (SMAW), Submerged Arc Welding (SAW), Metal Active Gas Welding (MAG), Metal Inert Gas Welding (MIG), Gas Tungsten Arc Welding (GTAW), Flux Core Arc Welding (FCAW).

It has been found out that the adjustment of details and the correction of finished structures constitute up to 30% of the total vessel hull manufacturing time in the case of arc welding techniques.

The application of laser technologies during ship construction decreases the cost of hull manufacturing by 30%, increases the production capacity by 10%, and reduces welding deformations by 30% compared to arc welding techniques.

Combined application of modern laser technologies under the condition of a high load degree of the production is capable to ensure the cost that can be compared with the cost of the same products manufactured with the help of conventional methods.

The combination of steels and composite materials in the structures to be adhesion-bonded can decrease the weight while preserving the strength, which will result in the manufacturing of lighter and stronger vessels. It is known that 10% decrease of vessel weight leads to 7% decrease of fuel consumption. Therewith, lighter upper structures improve vessel stability.

The efficiency of using new construction materials depends to a significant extent on the availability of corresponding joining technologies. Therefore, further investigations must be aimed at the development and implementation of effective techniques of welding and adhesion bonding of composite materials.

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