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# Assessment of the Applicability of Aluminum Alloy Welding Processes during the Prefabrication of Ship Structures Based on the Multi-Index Method

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**ABSTRACT**

The purpose of the paper is to evaluate the processes of welding aluminum alloys in terms of their applicability to the process of prefabrication of ship structures. The prefabrication process requires solving a number of problems related to the welding processes used (e.g. the problem of welding incompatibilities, deformations). Therefore, the key issue is to choose the right welding process, which is complex and difficult. It requires analysis of the process considering many points of view (e.g. technological, economic, security) in order to maximize the objectivity of the choice. Therefore, an attempt at a comprehensive view requires the formulation of a set of accurate evaluation criteria. The multi-indicator expert assessment presented in the article makes it possible to make such a choice. Currently used methods of welding aluminum alloys, both those from the group of conventional and innovative methods, were assessed. As a result of the analysis, the so-called technological hierarchy that allows to rank the assessed processes in terms of their suitability in the process of prefabrication of ship structures.

**Keywords**: prefabrication of ship structures, welding processes of aluminum alloys, evaluation criteria of welding processes, multi-index evaluation.

## INTRODUCTION

The welding processes of aluminum and its alloys are widely used in many industries. The specific properties of aluminum alloys (e.g. high relative strength, high corrosion resistance, high electrical and thermal resistance, easy machining, non-sparking and non-flammable) as well as extensive knowledge of welding technologies make aluminum welding available in many technological processes related to the construction of engineering structures, including ship structures (i.e. prefabrication processes of hull sections of vessels) [1–4].

Watercraft hull structures made of metal alloys, including, for example, yacht hulls made of aluminum alloys, consist of plating plates stiffened with a number of structural reinforcements in the form of frame and ordinary stiffeners, which are most often rolled sections, as well as brackets and other stiffening elements (Fig. 1a and b).

A large number of structural elements, and thus a large number of welded joints, often located at a short distance from each other and in difficult to perform conditions, resulting from the specificity of prefabrication of ship sections (Fig. 1c) make the selection of the appropriate welding process very important for the entire production process.

The knowledge about the weldability of aluminum alloys and its influence on a number of factors determining the quality of the joint, such as e.g. macroscopic features (irregularity in the joint, cracks, porosity, etc.), irregularities in the bead (cracks, porosity etc.), metallurgical defects (dendritic structure, segregations), in the heat affected zone (overaging, recrystallization structure etc.), stresses, is also important for the selection of the welding process, as shown in [5–10].

Despite the fact that currently, both in the production processes of typical structural elements (including ship structures) and in renovation works, conventional methods are commonly used for welding aluminum alloys, i.e. Tungsten Inert Gas (TIG) and Metal Inert Gas (MIG), more and more attention is paid to innovative welding processes using concentrated energy beams with a very high power density, such as: Laser beam welding (LBW), Hybrid welding (HLAW), [11, 12], and the modernization of conventional technologies towards their automation and robotization [13, 14] what brings measurable economic benefits [15]. Currently, the most developing aluminum welding method is friction stir welding (FSW) [16–19].

This creates new areas of activity in the field of fabrication of structures, especially with the use of materials that are very sensitive to thermal processes, such as aluminum alloys.

Each of the welding technologies used should ensure repeatability and the required quality of connections. In addition, technologies, regardless of the method of implementation of the process (guarantee, automatic, robotic), should also guarantee, among others: the required strength parameters of the connections made, the efficiency of the process, its safety and meet the conditions related to the specificity of the industry.

Therefore, an important issue is the analysis of the processes of welding materials (in this case aluminum and its alloys) in the context of determining the level of their suitability in a specific production process and confronting them with the processes already in use. In the literature, one can find comparative analyzes of aluminum welding methods [20, 21], which show that the compared elements (e.g. welding process control, incompatibilities in joints) differ depending on the process, and that there is no optimal process welding for all aluminum alloys.

Therefore a new type of analysis is proposed in the present paper, based on the multi-indicator method, with the use of individual set of criteria.

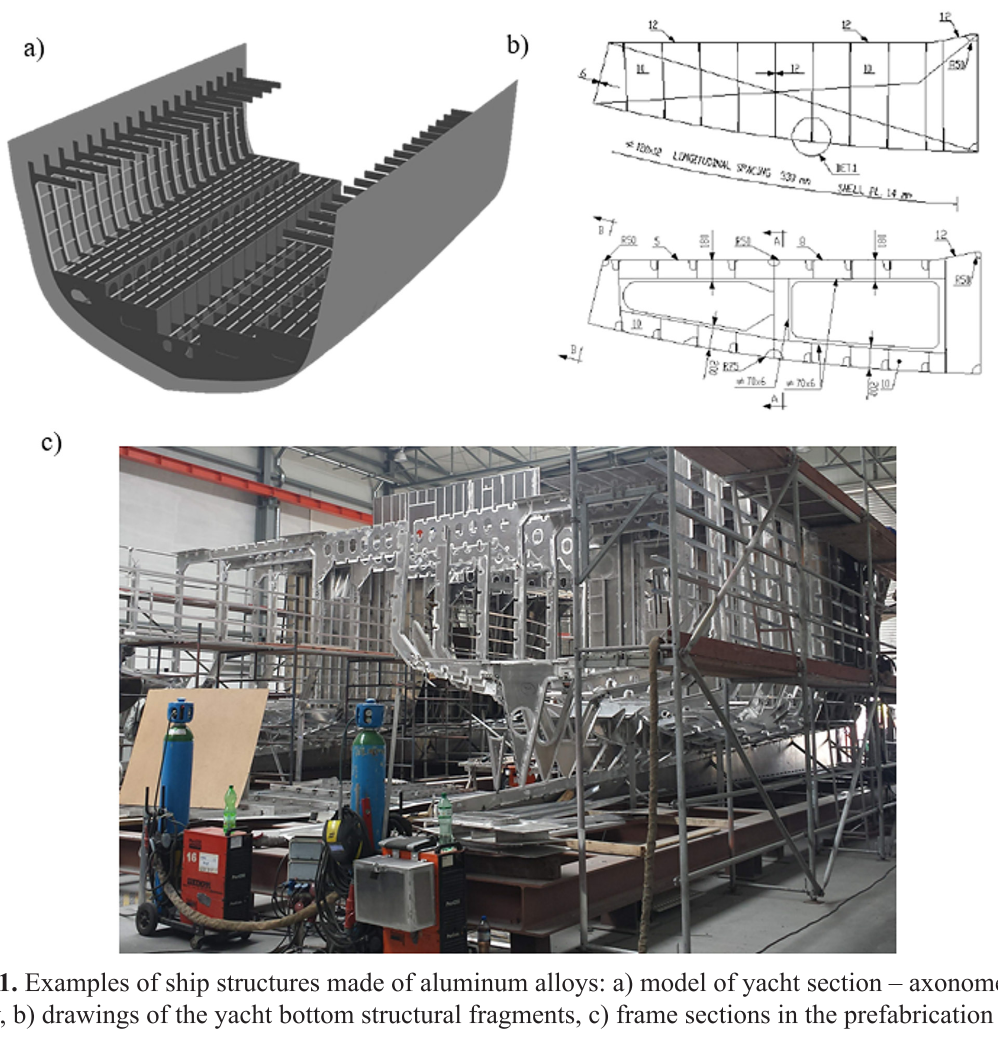


**Fig. 1.** Examples of ship structures made of aluminum alloys: a) model of yacht section – axonometric view, b) drawings of the yacht bottom structural fragments, c) frame sections in the prefabrication hall

## WELDING PROCESSES SUBJECT TO ASSESSMENT

The welding processes of aluminum alloys, subjected to a multi-index evaluation, were selected on the basis of the knowledge about the studied phenomenon contained in the specialist literature in the field of welding [22–26]. The following welding processes were selected for the analysis:

- arc welding with a tungsten electrode, welding with the TIG method,
- arc welding in an inert gas shield with a consumable electrode, MIG welding (in two variants, i.e. in a semi-automatic and robotic mode (MIG-ZR)),
- plasma welding (PAW),
- electron welding (EBW),
- laser welding (LBW),
- hybrid welding (HLAW),
- friction stir welding (FSW).

Text below contain only basic information on the analyzed welding processes, aimed at their identification. Detailed information is not the subject of the analysis falling within the scope of the subject of the article and is widely available in the literature.

In the TIG method, the tungsten electrode is placed in the nozzle to which the shielding gas is supplied. The electrode is connected to one pole of the power source and the workpiece to the other. After ignition of the arc, situated between the electrode and the workpiece, the workpiece is locally melted and the binder introduced simultaneously into the space of the arc. A weld is formed from the liquid metal.

MIG welding consists in fusing the welded metal and the consumable electrode material with the heat of an electric arc glowing between the consumable electrode and the object being welded, in an inert gas shield. Using the robotic mode of operation significantly improves the efficiency and quality of joints [27], also in the shipbuilding industry [28].

Plasma welding is similar to TIG welding. The important difference between these methods is that the arc plasma is narrowed by a nozzle to produce a high energy plasma jet, which achieves temperatures ranging from approx. 10.000 °C to 20.000 °C. The main advantage of the plasma arc is the almost constant cross section of the arc along its entire length.

Electron welding consists in melting the contact area of the joined objects with heat obtained by bombarding it in a vacuum with a concentrated beam of high-energy electrons, emitted from the heated and accelerated cathode with high voltage (approx. 30–200 kV). The tungsten cathode is heated by a current from the glow source. The electrons emitted from the cathode, focused in the form of a thin beam, move at high speed towards the anode and further towards the workpiece. The workpiece is moved on the cross table. The high concentration of the electron beam is achieved by means of a control electrode and magnetic lenses. The energy carrier in the welding process is the stream of electrons accelerated to a speed of about 200.000 km/s.

The laser welding process consists in fusing the contact area of the joined objects with the heat obtained as a result of bringing a concentrated beam of laser radiation with a very high power density to this area. Welding can be carried out by creating a weld pool, as in classic arc welding, or with full fusion of the joint in one pass or multilayer, with or without an additional material.

Hybrid welding involves the simultaneous use of two heat sources: a laser beam and an electric arc. Various combinations of heat sources can be used, e.g. $CO_2$ or Nd: YAG + TIG laser, $CO_2$ or Nd: YAG + MIG laser, $CO_2$ laser or Nd: YAG + plasma welding. The hybrid process requires a specialized stand ensuring precise mutual positioning of two heat sources. It is also possible to use special heads in which the laser beam is concentrically surrounded by an electric or plasma arc. As indicated in [29], the use of Nd-YAG laser welding, instead of the $CO_2$ laser, gives a lower reflectance, which allows for better weldability and fewer defects in the joint.

Friction stir welding is carried out in the solid state with an introduction of relatively small amount of heat to the joined metals in the presence not of mechanical force causing mutual pressure of the elements, but of the force exerted on the joined elements by a tool rotating in a metallic environment introduced into the area of the joint. This method of shaping and joining metals results in high-strength joints. In addition, the FSW method is ecological, does not produce ultraviolet radiation, gases and welding dust, and is energy-saving, because the heat is generated only at the joining point, inside the joined metals, and usually does not require the use of additional protective atmospheres [22].

**Table 1.** Assessment criteria for selected welding processes

| No. | Name | Symbol | Description |
|---|---|---|---|
| 1 | Functionality (work) criterion | K1 | It concerns the kinematic efficiency of welding devices (working movements performed), including the system of their work (e.g. manual, automatic) and related additional activities (e.g. the need to rotate the welded elements). |
| 2 | Performance (time) criterion | K2 | It concerns the efficiency of the assessed technology in the production process (i.e. in particular welding time). |
| 3 | Investment criterion | K3 | It concerns the degree of financial expenditure related to the introduction of technology into the production cycle (costs of equipment and maintenance of the position, staff qualifications). |
| 4 | Production cost criterion | K4 | It concerns the degree of consumption of media (energy and welding) necessary to carry out the process and the costs of labor and preparation of production. |
| 5 | Quality criterion (joint quality) | K5 | It concerns the estimated level of quality of the obtained welds, and thus the need to make corrections to remove welding imperfections. |
| 6 | Criterion of deformability (assembly suitability) | K6 | It concerns the estimated level of generation of welding deformations, and thus the need to carry out corrective works (mainly straightening). |
| 7 | Health and safety criterion | K7 | - |
| 8 | Risk criterion (ecological hazard) | K8 | It concerns the estimation of the emission of harmful substances emitted during the welding process to the environment. |
| 9 | Adaptability criterion | K9 | It concerns the possibility of adapting the welding technology to the specific working conditions of the shipbuilding industry (mainly stages of prefabrication of sections). |

## EVALUATION OF THE METHODS OF WELDING ALUMINUM ALLOYS USING THE MULTI-INDEX METHOD

The purpose of the evaluation of selected welding processes is to indicate their suitability in the process of prefabrication of ship structures made of aluminum alloys, i.e. the selection of the most technologically useful welding process.

The evaluation was made using so-called multi-criteria (multi-indicator) expert method. This method, described e.g. in [30], is based on several basic steps:

- defining the purpose of the analysis and selecting the "objects" to be assessed,
- formulating a set of criteria that define the sought set of features that describe selected "objects",
- defining the rules of assessment based on the established criteria,
- conducting an assessment for each of the analyzed "objects" and selecting the best of them.

The "objects" subjected to multi-criteria evaluation are selected welding processes. Nine criteria, presented in Table 1, have been selected for the assessment of individual welding processes, which are believed suitable for reliable achievement of the objective of the presented evaluation.

Selected welding processes were assessed independently according to the criteria (Table 1) on a point scale from 0 to 5. The higher the rating, the greater the suitability of a given welding process. All criteria have been made dimensionless by dividing them by the maximum number of points that can be given to a specific criterion, i.e. by 5.

A nine-parameter radar diagram was plotted for each welding process (Fig. 2). The plot area is a generalized criterion for assessing the suitability of the welding process. Ideally, each of the 9 criteria has a dimensionless value of 1. The area of the radar plot for an ideal object is 2.891. The assessment of the usefulness of the welding process, depending on the area "p" of the radar diagram, is presented in Table 2.

The results of the multi-criteria evaluation for the analysis are presented in Table 3 and illustrated in Fig. 2 and Fig. 3. Figure 2 presents a summary of radar charts for all assessed welding processes, illustrating all the obtained assessment states (according to Table 3). Figura 3 presents a summary of the field values of radar diagrams describing the level of technological suitability of the assessed welding processes.

Analysing the obtained results (Table 3, Fig. 2 and Fig. 3), we can conclude that:

**Table 2.** Evaluation of the usefulness of the welding process depending on the surface of the radar chart

| No. | Usefulness of the welding process | Radar chart area value [-] |
|---|---|---|
| 1 | Very good | $2.169 < p$ |
| 2 | Good | $1.446 < p \leq 2.169$ |
| 3 | Acceptable | $0.723 < p \leq 1.446$ |
| 4 | Bad | $p < 0.723$ |

**Table 3.** Results of assessment of usefulness of aluminum welding processes

| No. | Assessment criterion | Assessment on a point scale (from 0 to 5) for selected welding processes | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | TIG | MIG | PAW | EBW | LBW | HLAW | MIG-ZR | FSW |
| 1 | Functionality (work) criterion | 3 | 3 | 2 | 2 | 3 | 3 | 4 | 2 |
| 2 | Performance (time) criterion | 2 | 3 | 4 | 5 | 5 | 5 | 5 | 4 |
| 3 | Investment criterion | 2 | 3 | 3 | 5 | 4 | 4 | 4 | 3 |
| 4 | Production cost criterion | 3 | 3 | 3 | 1 | 2 | 2 | 3 | 4 |
| 5 | Quality criterion (joint quality) | 3 | 2 | 4 | 5 | 5 | 5 | 4 | 5 |
| 6 | Criterion of deformability (assembly suitability) | 3 | 2 | 4 | 5 | 5 | 5 | 3 | 5 |
| 7 | Health and safety criterion | 2 | 2 | 3 | 5 | 4 | 4 | 4 | 4 |
| 8 | Risk criterion (ecological hazard) | 2 | 2 | 3 | 5 | 4 | 3 | 2 | 5 |
| 9 | Adaptability criterion | 2 | 4 | 3 | 1 | 4 | 4 | 4 | 3 |
| 10 | Field area radar chart, [-] | 0.694 | 0.835 | 1.195 | 1.632 | 1.825 | 1.722 | 1.542 | 1.773 |
| 11 | Area share of assessed welding technology to area of ideal chart, [%] | 24.003 | 28.892 | 41.338 | 56.451 | 63.118 | 59.562 | 53.339 | 61.340 |
| 12 | Technological hierarchy | 8 | 7 | 6 | 4 | 1 | 3 | 5 | 2 |

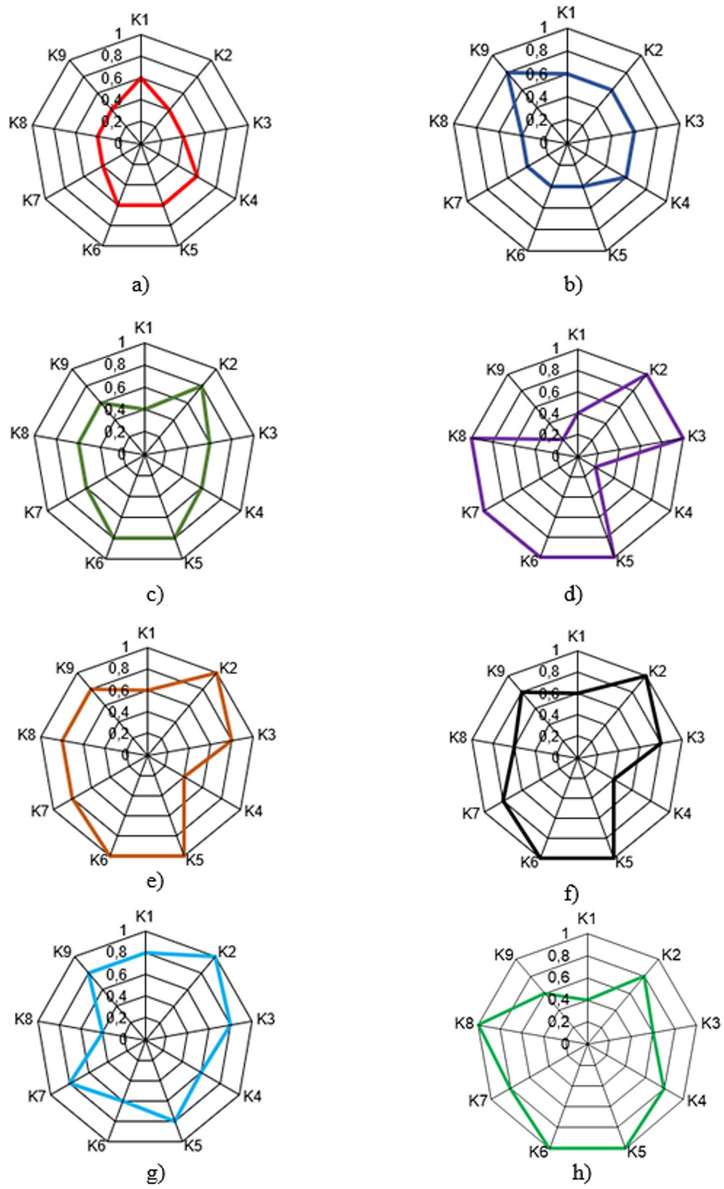


**Fig. 2.** Summary of radar charts for assessed welding processes:
a) TIG, b) MIG, c) PAW, d) EBW, e) LBW, f) HLAW, g) MIG-ZR, h) FSW

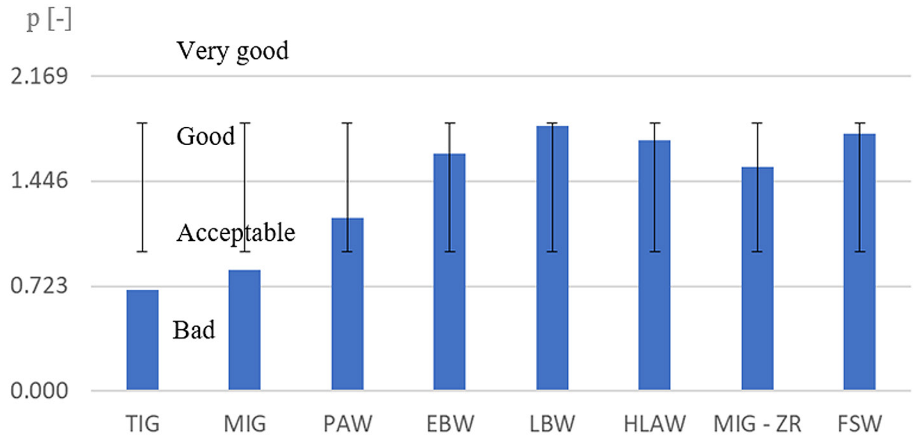


**Fig. 3.** Summary of field values of radar charts describing usefulness level of assessed welding processes

- most of the welding processes assessed (i.e. five out of eight) were suitably good,
- two welding processes can be estimated as acceptable,
- one process has been given a bad level of usefulness,
- none of the welding processes assessed were very suitably usable.

## CONCLUSIONS

The presented expert analysis allows for the introduction of the so-called technological hierarchy, allowing for ranking of the assessed welding processes, from the least to the most significant, in terms of their usefulness for joining elements of the hull structure of vessels made of aluminum alloys.

The fact that none of the assessed welding processes achieved the highest level of suitability may indicate the correct selection of the evaluation criteria and its substantive correctness.

It has been found that in the area determining a good level of usefulness of welding processes, there are four technologies that can be classified as innovative (EBW, LBW, HLAW and FSW) and one conventional technology (modernized, MIG-ZR) with the use of an articulated robot. The differences between the shares of the area of radar charts of individual technologies to the area of the best chart are negligible, i.e. at the level of: 3 ÷ 15% (Table 3, line 11) (precise values are as follows: 2.82% between LBW and FSW, 5.63% between LBW and HLAW, 10.5% between LBW and EBW as well as 15.49% between LBW and MIG-ZR). This proves that there is definitely no leading welding technology, and especially LBW, FSW and HLAW (from the technological hierarchy) can be treated as equivalent.

The next two welding processes, PAW and MIG, located in the technological hierarchy in the sixth and seventh places, respectively, have obtained a sufficient level of usefulness. They differ by 0.36 p of the surface area of the radar chart. It should be remembered that MIG belongs to conventional technologies, while PAW, especially in the mechanized system, can be classified as a technology on the "borderline" of innovative technologies. Therefore, it can be assumed with a high degree of probability that the use of MIG technology in an automated system would give a similar position in the technological hierarchy to the assessed PAW.

The conventional TIG process obtained a bad usefulness level, but it should be noted that it was only 0.029 p less than the value of the radar chart surface area down to the good level. This fact proves that the boundaries between individual areas that determine the level of usefulness of a given welding technology should be treated flexibly and considered depending on the individual situation, related primarily to the assumed prefabrication technology and established quality requirements.

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