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EFFICIENCY AND QUALITY OF THE ALUMINIUM ALLOY WELDING PROCESS DEPENDING ON THE METHOD USED

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Purpose: The aim of this article is to analyse the criteria for selecting a welding method for aluminium alloys from the two most popular conventional methods: Metal Inert Gas (MIG) and Tungsten Inert Gas (TIG) and to assess their impact on the efficiency, quality and management of the welding process.
Design/methodology/approach: The results presented in the article were obtained by analyzing the available literature as well as our own practical experience related to the management of production processes, taking into account quality and operational aspects.
Findings: The selection of the welding method for aluminium alloys depends on many factors, including quality requirements and effective management of the production process. The criteria for selecting welding methods have been systematized and a comparative analysis of their impact on the efficiency and quality of welded joints has been conducted.
Practical implications: The choice of welding method for aluminium alloys is influenced not only by technical aspects, but also by economic, management and quality aspects. Proper process management and awareness of the limitations, advantages and disadvantages of individual welding methods allows obtaining aluminium joints of the required quality and optimization of operating costs.
Originality/value: The original achievement of the analysis is the establishment of comprehensive criteria for the selection of welding methods, taking into account quality management and the production process. The results can be useful to designers, manufacturers and managers, allowing for more effective management of the quality and efficiency of welding processes.
Keywords: welded joint, aluminium alloys, MIG, TIG, process management, quality management.
Category of the paper: Technical and managerial paper.

1. Introduction

Aluminium is a strong and lightweight element, with a density of 2.7 kg/dm^3 – 3 times less than steel. It is characterized by good electrical and thermal conductivity, high corrosion resistance, ease of forming, low price and can be recycled many times (Raabe et al., 2022).

Pure aluminium has limited technical use. By adding other elements to aluminium, alloys are created, which after appropriate heat treatment have very good mechanical parameters (Varshney, Kumar, 2021). The symbols of aluminium alloys are marked according to the standard (PN-EN 573-1:2006).

Due to their properties, aluminium alloys are used in various industries – they are used to make beverage cans, parts of various devices, car and ship components (Xie et al., 2024), high-speed trains (Deng et al., 2024) and airplane components (Li et al., 2023). Aluminium alloys have found wide application in civil engineering, both for the production of load-bearing structures, facades, and window, door and gate components (Kwiatkowski, 2011, 2012). Aluminium structures are designed based on Eurocode 9 (PN-EN 1999-1-1:2011). The use of lightweight aluminium structures saves energy and reduces pollutant emissions. This is facilitated by the use of environmental management systems in enterprises (PN-EN ISO 14001:2015-09).

The wide use of aluminium alloys in various industries often requires the use of welded joints. Unfortunately, the process of welding aluminium alloys is much more difficult than welding steel and requires not only the right selection of the welding method, but also highly qualified welders. Therefore, the development of efficient methods of welding structures made of aluminium alloys while obtaining high-quality joints is a current research topic. In order to ensure the proper quality of products and welded joints made of aluminium alloys, it is worth introducing quality management systems (PN-EN ISO 9001:2015-10) in companies involved in their production. This allows the efficiency of the welding process to be increased and, consequently, the efficiency of the company.

Efficiency is of great importance in management, as it affects various aspects of a company's operations: it allows to reduce costs, improve the quality of products or services, or increase production efficiency. At the same time, it means that the company is able to meet the expectations of its customers by producing products or providing services of high quality in accordance with standards.

In industrial practice, the choice of welding method for aluminium alloys is often limited by the welding equipment available to the company. These are usually welders using conventional MIG or TIG methods. Even if the company has both types of welders, it happens that the choice of method is random, usually resulting from a lack of knowledge of which method is more suitable for making a specific welded joint. The basis for comparing these welding methods was to identify the differences between them that affect the efficiency of using a given method.

2. Welding of aluminium alloys

The general guidelines for shaping welded joints of aluminium alloys are analogous to those for steel joints (Kubicki, 2022, 2023; Kubicki, Wojsyk, 2022). Arc welded joints in aluminium alloys should be made in accordance with the standard (PN-EN ISO 10042:2018-09). The properties of aluminium alloys affect the way welds are made and their weldability. All aluminium alloys from groups 1XXX, 3XXX, 4XXX, 5XXX and 6XXX can be arc welded. However, most alloys from groups 2XXX and 7XXX cannot be properly joined by arc welding, as they will crack during welding (AWS D1.2/D1.2M:2014). Technical aspects have a fundamental impact on the rational and economical design and execution of such joints. Due to the material properties, welding aluminium alloys requires specialist knowledge and high skills from welders.

Aluminium has a relatively low melting point (approx. 660°C), and its alloys, depending on the additives introduced, usually lower (even approx. 470°C). Only a few alloys of some series have a slightly higher melting point than pure aluminium. The classification and designation of casting alloys is given in the standard (PN-EN 1706+A1:2022-01), and alloys for plastic processing in the standard (PN-EN 573-3+A2:2024-06). On the surface of aluminium and its alloys, difficult-to-melt Al_2O_3 oxide films are formed, which do not melt until about 2050°C. On the one hand, they protect the metal itself against corrosion, on the other hand, they make welding very difficult. Additionally, due to their hygroscopicity, oxides can absorb moisture from the air, which increases the porosity of the joint. Therefore, immediately before welding it is necessary to remove oxides with a brass wire brush and degrease the material.

The weldability of aluminium alloys is influenced by many factors, but the most important one is the addition of alloying elements. Generally, silicon and magnesium-silicon alloys are characterized by good weldability.

Traditional MIG (Ferenc, 2018) or TIG (Ferenc, 2023) methods are usually used for welding aluminium alloys. The development of aluminium alloy welding methods expands the scope of application, eliminating the limitations and disadvantages of conventional methods. However, this is usually associated with an increase in the costs associated with the purchase of specialized equipment. Among modern methods of welding aluminium alloys, the following can be distinguished:

- pulsed CMT-MIG – cold metal transfer arc-metal inert gas (Brukner, 2009; Rajendran et al., 2024),
- double pulse MIG (Ye et al., 2024),
- high-speed MIG welding with external magnetic fields (Wu et al., 2022),
- pulsed hybrid laser (Wang M. et al., 2025),
- pulsed Laser-MIG hybrid welding (Jia et al., 2022),
- STT – surface tension transfer arc welding (Nagasai et al., 2023),

- variable-polarity plasma arc welding (Wang, X. et al., 2024),
- FSW – friction stir welded (Abolusoro, 2024; He et al., 2011; Lacki, Derlatka, 2013; Patel, Arora, 2024).

Some methods allow joining aluminium alloys with other metals, e.g. with steel (Chen, 2024; Feizollahi, Moghadam, 2023; Ghari et al., 2024), with copper (Eljasi et al., 2023) or with titanium (Shehabeldeen et al., 2021, Zhang et al., 2022).

3. Criteria for selecting a welding method for aluminium alloys

This analysis of the criteria for selecting welding methods for aluminium and its alloys covers only the two most popular and most accessible welding methods – MIG and TIG. Welding using these methods has been discussed in textbooks (Ferenc, 2018, 2023). Both methods are commonly used, but they are not always properly selected for specific welded joints.

There are certain features that both methods have in common:

- weldability of the same types and grades of aluminium alloys,
- use of the same shielding gases (mainly argon, rarely helium and mixtures of these gases),
- practically rare use of forming gas,
- possibility of welding in all positions,
- similar costs of welding consumables,
- limited outdoor applicability due to air movement that can disperse the shielding gas – welding tents required,
- analogous method of edge preparation.

This does not mean, however, that these methods are interchangeable in every case. Depending on the type of joint, thickness of the welded materials and quality requirements, the appropriate method should be selected.

Examples of MIG welds are shown in the figures below (Figure 1-5). Due to the specificity of aluminium alloys, weld imperfections occur more often than in steel. For butt joints of sheets (Figure 1), you can see especially from the side of the weld root the place where welding was interrupted and resumed.

a) 
b) 
c) 

Figure 1. Butt joint of 1 mm thick sheets using the MIG method: a) weld face, b) weld root, c) metallographic section.

Source: own study.

This effect is not observed in lap joints (Figure 2), because there is no penetration to the weld root. However, in several places, a dark coating is visible, resulting from the condensation of magnesium vapors. This defect occurs when welding with the MIG method using Al-Mg wire.

a) 
b) 

c) 

Figure 2. Lap joint of 1 and 2 mm thick sheets using the MIG method: a) weld face, b) weld root, c) metallographic section.

Source: own study.

Although the TIG method is recommended for butt joints of aluminium pipes, they can also be welded using the MIG method, achieving deeper penetration. The cross-section (Figure 3b) shows how deep penetration can be achieved with this method.

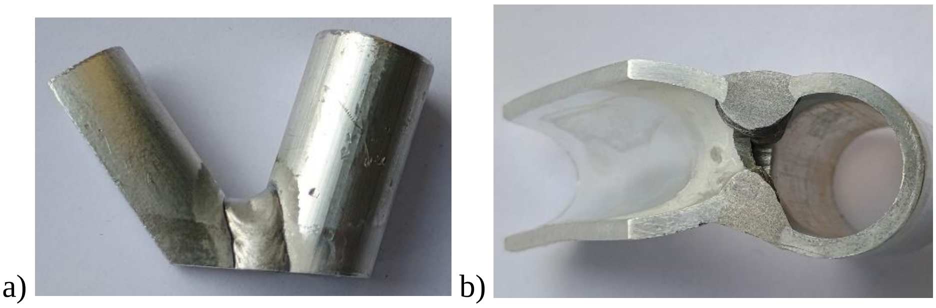

Figure 3. Pipe-to-pipe connection using the MIG method: a) weld face, b) joint cross-section.

Source: own study.

The MIG method is also used to weld other elements, such as sections, aluminium castings, or pipes with sheet metal. With the proper setting of welding parameters, a correct joint can be obtained without narrowing the pipe lumen (Figure 4).

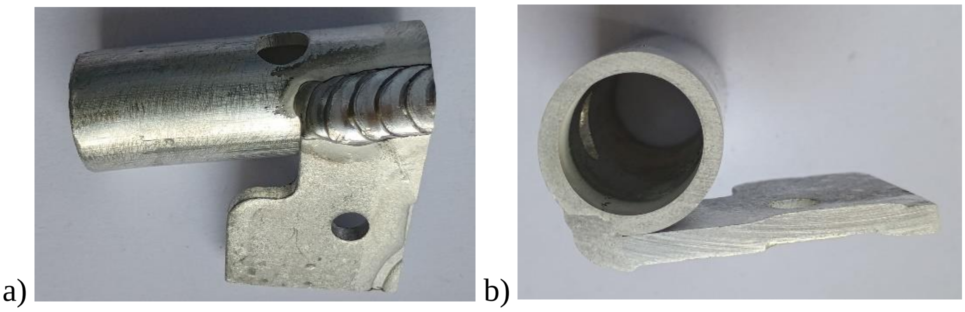

Figure 4. Pipe-to-sheet metal connection using the MIG method: a) weld face, b) joint cross-section.

Source: own study.

Due to the possibility of obtaining deeper penetration, the MIG method is also used in T-joints (Figure 5).

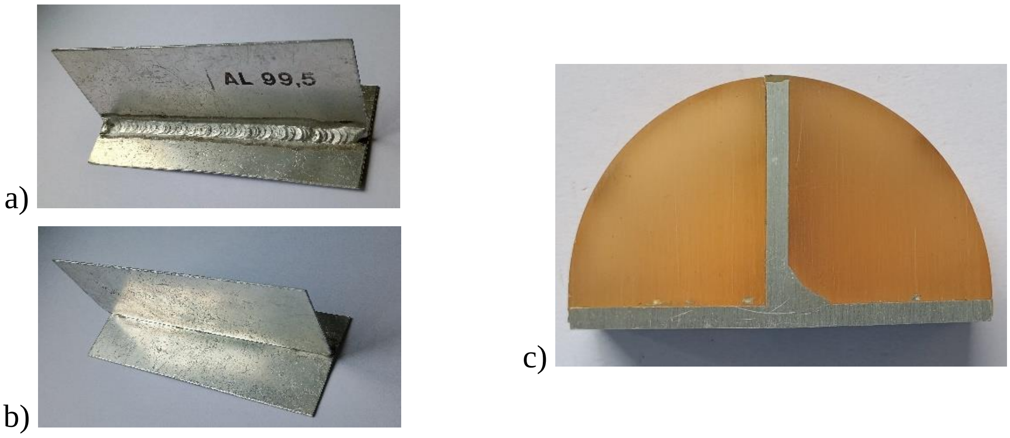

Figure 5. T-joint with single-sided fillet weld of 1 mm thick sheets using the MIG method: a) weld face, b) weld root, c) metallographic section.

Source: own study.

TIG joints have a more limited scope. They are generally made for thinner elements, for which high quality of the weld is required. A butt joint of sheets made by the TIG method is shown in (Figure 6). A characteristic end of the weld in the form of a crater can be observed. To avoid cracks in this place, run-off plates are used or the crater is cut out and re-welded. Modern welding machines have a function of filling the crater by gradually reducing the welding power at the end of the work.

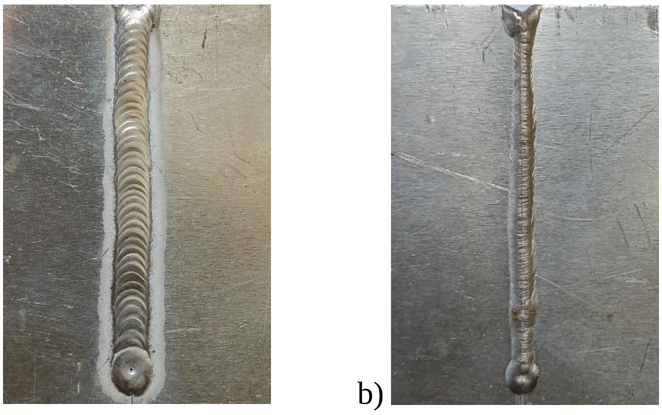

Figure 6. Butt joint of 2 mm thick sheets using the TIG method: a) weld face, b) weld root.

Source: own study.

In all joints, regardless of the welding method used, the heat-affected zone (HAZ) can be observed from the weld face as an area of light, matt discoloration. In this zone, the mechanical properties of the base material deteriorate (Aune et al., 2024).

Conventional MIG and TIG methods differ from each other in certain features that may determine the right choice. Table 1 presents the criteria for selecting a welding method.

Table 1.
Criteria for selecting MIG and TIG welding methods

Selection criterion	Method	
	MIG	TIG
Minimum joint thickness	1 mm	0,5 mm
Maximum thickness	25 mm with argon, 75 mm with helium	6 mm with argon, 10-18 mm with helium
Pipe root welding	not recommended	recommended
T-joint, Corner joint, Cruciform	deeper penetration of fillet weld roots	difficult to penetrate into corners and into the roots of fillet welds
Cost of welding equipment	high	relatively low
Costs of weld filler materials and gas	comparable	comparable
Possibility of automating the welding process	very good	limited
Quality of welds	high	very high
Cleanliness of welds	high	very high
Welder qualifications	average	high
Cleaning the edges of the joint before welding	the necessity of removing oxides mechanically and/or chemically	the necessity of very thorough cleaning
Cleaning the wire before welding	practically impossible	only when high quality is required

Cont. table 1.

Welding current type	direct current (DC+)	mainly alternating current (AC); exceptionally direct current (DC+, DC-) for thicker joints – then only helium as a shielding gas
Oxide film removal intensity	high – negative polarity on the material	sufficient for AC and negative polarity on the material
Welding deformations	less	greater
Generation of weld spatter	occurs when welding parameters are not selected correctly	does not occur
Susceptibility to lack of fusion	high	moderate
Dark coating formation	occurs mainly when welding with Al-Mg wire	practically does not occur
Reduction of joint strength in the heat-affected zone of the base metal	slightly smaller and narrower	slightly larger and wider
Interference with other electronic devices	none	may be caused by the ionizer

Note. MIG: metal inert gas welding; TIG, tungsten inert gas welding; AC: alternating current; DC: direct current.

Source: (AWS D1.2/D1.2M:2014; Ferenc, 2018, 2023; Olabode et al., 2013), own study.

4. Conclusion

Joining elements made of aluminium alloys by welding is the only method that simultaneously meets the three characteristics of a good connection, namely strength, tightness and durability. Therefore, such welded connections are often used in construction to make roofs, canopies and shell structures.

The choice of the conventional welding method for aluminium alloys is not always simple, although it is often limited to the use of the MIG method for thicker elements and TIG for thinner ones. However, this basic criterion is not the only one. The type of joint often favors the adoption of one of the methods, e.g. for butt joints of pipes – TIG, and for joints using fillet welds – MIG. The choice of the method is usually associated with the acceptance of a compromise between the higher quality of the weld and aesthetics in the TIG method and the higher speed of execution in the MIG method. This inconvenience can be eliminated by using the pulsed MIG method. In addition, the TIG method does not cause spatter, but it requires higher qualifications from the welder.

If the efficiency of the welding process is limited only to reducing costs, then the MIG method will be more beneficial due to the higher welding speed. Shortening the time of welds and lower requirements for welders' skills significantly affect the costs of the entire process. However, if ensuring high aesthetics of welded joints, without dark deposits and spatter, of high cleanliness and quality, is more important, then the choice of the TIG method will be more appropriate. It should also be taken into account that the one-time cost of purchasing welding equipment with comparable parameters is relatively lower for the TIG method.

It seems that future research should focus on pulsed MIG welding methods. Their use can improve efficiency (higher welding speed than TIG) and quality of aluminium alloy welding processes (comparable to TIG) at relatively the lowest cost.

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