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TIG WELDING OF TITANIUM ALLOY TI-6AL-4V FOR AUTOMOTIVE APPLICATIONS

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Purpose: The main novelty of the paper is to present the Ti alloy welding for automotive application. Welding titanium is a difficult task. The aim of the article is to develop the MIG (Metal Inert Gas) welding process for titanium alloys and to indicate the correct process parameters.
Design/methodology/approach: Various parameters of the titanium alloy welding process were tested and then the quality of the obtained joint was checked by the mechanical tests.
Findings: The correct process parameters were determined and the properties of the joint were compared with the properties of the base material.
Research limitations/implications: In the future, it can be suggested to investigate the effect of modified shielding gas mixtures (Ar-He) for the MIG welding.
Practical implications: The proposed process innovation will result in savings of production cost, because titanium and its alloys are suggested to be welded in a vacuum, which is a much more expensive process.
Social implications: By modifying the process, environmental protection is not impaired, EU directives on reducing CO_2 emissions (carbon footprint) are fulfilled.
Originality/value: It is to propose a new solution in automotive industry. The article is especially addressed to manufacturers of titanium alloys for means of transport.
Keywords: automotive, titanium, welding, transport, production savings.
Category of the paper: Research paper.

1. Introduction

The costs of titanium welding can be significantly reduced by several different methods, with an emphasis on process optimization, minimizing material losses and selecting appropriate welding technologies. The most important aspects that can help you reduce costs are following (Yee et al., 2023):

1. Optimization of welding processes - Selecting appropriate welding parameters, such as current, voltage and welding speed, allows you to minimize energy consumption and reduce the amount of impurities.
2. Use of pulse welding - Compared to traditional welding, pulse welding can reduce energy consumption and reduce the amount of heat introduced into the material, which is important when working with titanium, which is susceptible to oxidation.
3. Protection against oxidation - Titanium easily reacts with oxygen, which affects its properties and increases welding costs (due to the need for rework). The use of an atmosphere of inert gases (e.g. argon) allows to limit this reaction, which results in higher quality of welds and lower costs.
4. Process automation – Automation of titanium welding, e.g. using welding robots, allows for repeatability and precision, which reduces the number of defective welds and the need for corrections.
5. Minimizing material thickness – In applications where it is possible to reduce the thickness of titanium, material consumption and welding costs can be reduced. However, careful analyzes must be carried out to maintain the appropriate strength of the structure.
6. Modern welding technologies – Techniques such as laser or electron welding make it possible to achieve high-quality welds with lower energy costs and smaller material deformations.

The paper presents the results of various TIG (Tungsten Inert Gas) welding tests for titanium alloy Ti-6Al-4V. Titanium welding is a process used when working with metals that are difficult to weld because it allows for high-quality and precise connections. Titanium is characterized by high strength and corrosion resistance, making it an ideal material for applications in aviation and automotive. However, TIG welding of titanium requires special conditions to avoid problems such as oxidation and weld brittleness. Titanium and its alloys have better anti-corrosion properties than steel, but they are much more difficult to weld (Jaewson et al., 2011; Darabi et al., 2016). Titanium reacts very easily with oxygen, nitrogen and hydrogen, especially at high temperatures, which can lead to brittleness and loss of mechanical properties of the joint. Therefore, during welding, effective protection with shielding gas (usually argon or helium) is necessary (Golański et al., 2018, pp. 53-63; Skowrońska et al., 2017, pp. 104-111). The use of high purity argon (at least 99.995%) is necessary to avoid gaseous impurities. Helium is sometimes used as an additive gas because it improves arc penetration and stability, but the medium is less popular due to its higher cost. When welding steel, there are no such stringent requirements (Fydrych, Łabanowski et al., 2013; Shwachko et al., 2000).

The deciding TIG welding parameters are:

- type of wires,
- composition of gas mixtures (Ar-He) in TIG welding,
- pre-heating temperature.

The surface of welded titanium must be perfectly clean - any contamination, fat or oxide residues may deteriorate the quality of the weld. It is recommended to clean the surface with isopropyl alcohol or special preparations. The tungsten electrode must be properly sharpened and clean (Rehman et al., 2021).

Welding titanium requires relatively low current because the material has low thermal conductivity, which means it heats up quickly. Overload may lead to melting or deformation of the material. Welding too slowly may result in excessive heating, which promotes oxidation, while welding too quickly may result in incomplete penetration (Faraji et al., 2021).

Properly selected welding speed allows you to obtain a smooth weld. In addition to the main shielding gas, additional protective shields (e.g. shielding chambers or back surface protection tools) are often used to prevent oxidation of the weld at the interface (Li et al., 2023). Titanium has two allotropic varieties (alpha hcp and beta bcc). Ti-6Al-4V alloy is the most widely used and most popular titanium alloy, containing aluminum (6%) and vanadium (4%). It is strong, resistant to corrosion and can be easily welded and heat treated. Thanks to its universal properties, it is used in various industries. This alloy has a two-phase ($\alpha + \beta$) structure (Piao et al., 2023).

7. Materials

For titanium alloy Ti-6Al-4V welding the austenitic electrode wire 309LSi was selected. For titanium alloy welding the TIG (Tungsten Inert Gas) method, specialized rods are used, which are selected depending on the type of alloy and the mechanical requirements of the finished weld. Here are some of the most commonly used titanium alloy welding rods:

- Grade 5 titanium rods (Ti-6Al-4V) – is the most popular titanium alloy used in industry, due to its excellent mechanical properties and fatigue strength.
- Grade 23 titanium rods (Ti-6Al-4V ELI) – is a variant of the Grade 5 alloy with a reduced level of impurities, especially oxygen.

The main direction of research was the modification of shielding gas mixtures in the TIG process containing Ar and He and two types of rods (Grade 5 and Grade 23). Preheating before TIG welding of titanium alloys is usually kept to a minimum or often omitted because titanium has a low thermal conductivity, which causes the heat to concentrate in the welding area. A thickness of weld was 2 mm. Table 1 presents the mechanical properties of Ti-6Al-4V alloy.

Table 1.
Tensile strength of tested material

Ti alloy	YS, MPa	UTS, MPa
Ti-6Al-4V	820	960

The mechanical properties of the alloy results from their various chemical composition (Table 2). These good mechanical properties of the alloy are the result of the chemical composition, which affects the structure of the alloy (alpha + beta). The alpha phase is responsible for good plastic properties, and the beta phase guarantees high tensile strength.

Table 2.
Chemical composition of tested grades of steel

Ti alloy	C	Al	V	Fe	O	N	Cr	Mo	Ti
Ti-6Al-4V	0.07	5.9	4.1	0.2	0.01	0.04	0.4	0.6	bal

The analysis of the table shows that the alloy contains alpha phase stabilizers: Al, and O, N, C (which are treated rather as impurities in titanium alloys) and beta phase stabilizers, which are primarily vanadium and Fe, Mo, Cr. The main alloying elements are Al and V, which is consistent with the symbol of the alloy.

It was decided to realize welding process of 2 mm thickness without chamfering. The rod diameter in all cases was 2 mm. The weld was formed as single-pass. On the root side, the joint was protected by a ceramic forming backing.

At the beginning of welding process, the current and the voltage parameters were suggested:

- welding current: 106 A,
- arc voltage: 22 V.

Other important welding parameters were determined as follow:

- welding speed: 60 mm/min,
- shielding gas flow: 17 dm^3/min.

The joints were made with a several combinations. The most important element of investigation included checking the preheating temperature and selecting of proper shielding gas mixture for TIG welding process containing:

- Ar-18% - 5% He.
- Ar-18% - 10% He.
- Ar-18% - 15% He.

The use of high purity argon and helium (at least 99.995%) is necessary to avoid gaseous impurities. Helium is sometimes used as an additive gas because it improves penetration and arc stability, but there is no clear opinion on the most favorable He content in Ar-He mixtures. Purpose of adding helium to the gas mixture when welding titanium:

1. Increasing the energy of the welding arc - helium has a higher thermal conductivity than argon, which results in a higher arc temperature.
2. This results in better material penetration and a more stable welding process.

Also a very important element of the research was to eliminate preheating temperature.

8. Methods

After the welding process with various parameters, non-destructive test (NDT) and also some destructive tests (DT) were carried out to assess the best quality of the joints.

Initially some NDT were carried out:

- VT - visual test corresponded with → PN-EN ISO-17638 standard.

Then, some DT testing were carried out:

- tensile strength → PN-EN ISO 527-1 standard,
- bending test → PN-EN ISO 7438 standard.

9. Results and discussion

The dissimilar joints were made using two rods (Grade 5 and Grade 23) and three different of shielding gas mixtures without pre-heating temperature. In total, 6 different welds were made, marked with samples from E1 to E6 (tab. 4).

Table 4.
Samples designations

Sample	Shielding gas mixture	rod
E1	Ar-18% - 5% He	Grade 5
E2	Ar-18% - 5% He	Grade 23
E3	Ar-18% - 10% He	Grade 5
E4	Ar-18% - 10% He	Grade 23
E5	Ar-18% - 15% He	Grade 5
E6	Ar-18% - 15% He	Grade 23

NDT tests were performed for all samples (E1-E6) after welding process. Most of the samples (E2, E3, E4, E6) were defect-free (column rows marked in green colour), but two samples (E1, E5) were made incorrectly (column rows marked in pink colour). The NDT results with comments on the observations during inspection are presented in Table 5.

Table 5.
NDT results for tested dissimilar welds

Sample	Observation
E1	Small cracking in HAZ
E2	Correct weld, defect free, correct form and dimension of HAZ
E3	Correct weld, defect free, correct form and dimension of HAZ
E4	Correct weld, defect free, correct form and dimension of HAZ
E5	Small cracking in weld from the face and root sides
E6	Correct weld, defect free, correct form and dimension of HAZ

It was found that the choice of Grade 23 rod gives better results than Grade 5 rod. In turn, the helium content of 10% in the argon shielding mixture guarantees a correct joint. Helium (in range 10%) improves the flow of shielding gas, which can help keep the weld zone clean, reducing the risk of contaminants (such as nitrogen, oxygen or hydrogen) that can lead to weld defects such as pores. Helium helps stabilize the welding arc (samples E3, E4), which is important in the TIG process, where precise control of the arc is key to obtaining a high-quality weld. However, too high a helium content in the shielding argon mixture may stop the electric arc stabilization process and may lead to deterioration of the joint properties (sample E5). Titanium can easily form oxide and nitride inclusions, so it is important that the welding zone is properly protected. The next element of the research was to perform a tensile strength test. Only samples that tested positive in NDT tests were taken into account for destructive testing (E2, E3, E4, E6). The tensile strength tests were performed at room temperature (19°C). Table 7 shows the tensile strength (UTS) of the joints.

Table 7.
Tensile strength of joints

Sample	UTS [MPa]
E2	679
E3	718
E4	705
E6	687

The data from the tab. 7 indicate that it is possible to achieve high tensile strength of the tested joints over the 650 MPa. It was noticed that the joint made of Grade 5 rod had the best strength, which indicates that small impurities in the rod can strengthen the weld. This is a very interesting observation also from the point of view of savings in production, because Grade 5 rod is 20% cheaper than Grade 23.

As the last part of the article a bending tests was carried out. Measurements were done from the face and from the root sides of the joint. A bending test was performed at ambient temperature. The observation and results of bending test are presented in Table 8.

Table 8.
Bending test of dissimilar weld

Sample	Face side	Root side
E2	No cracks	No cracks
E3	No cracks	No cracks
E4	No cracks	No cracks
E6	No cracks	No cracks

The bending tests were very positive, no cracks were observed in all samples. This proves very good properties of the thin-walled titanium alloy joint.

10. Summary

The article presents the principles of welding the Ti-4Al-6 alloy used in the automotive industry in terms of cost savings. Various parameters of the TIG welding process were analyzed. The quality of joints welded using non-destructive and destructive methods was assessed. The influence of various rods and shielding gas mixtures was tested. TIG welding can effectively replace the much more expensive welding process in a vacuum chamber. Joints with very good mechanical properties were obtained.

Based on the research study, the following conclusions were given:

1. Welding of alloy Ti-4Al-4V using TIG method allows for process savings.
2. All welding parameters should be selected very precisely.
3. The most important parameters of the titanium alloy are chemical composition of rod and shielding gas mixture.
4. The best welding results were obtained when simultaneously:
   - the preheating temperature was not used,
   - the shielding gas mixture should contain Ar-18% - 10% He,
   - an electrode wire should have austenite structure.

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