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ECONOMIC ASPECTS OF OF TITANIUM ALLOY TI-5AL-2.5SN WELDING FOR AVIATION APPLICATIONS

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Purpose: Novelty of the paper is to present the Ti alloy welding for aeronautic application. Welding titanium is treated as a difficultprocedure. The aim of the article is to develop the TIG (Tungstan Inert Gas) welding process for titanium alloys instead of much more expensive process of welding in vacuum chamber
Design/methodology/approach: Main parameters of the titanium alloy welding process were tested and then the quality of the obtained joint was checked by the mechanical tests.
Findings: Welding parameters were determined without carring out the process in vacuum chamber that is much more expensive and energy-intensive process.
Research limitations/implications: It was suggested to investigate the effect of modified shielding gas mixtures (Ar-He) for the TIG process.
Practical implications: The proposed process innovation will result in savings of production cost, because titanium alloys are mainly welded in a vacuum chamber, which is more expensive process.
Social implications: Vacuum chamber in the welding process allows for energy savings.
Originality/value: It is to propose a new solution in aeronautic industry. The article is especially addressed to manufacturers of titanium alloys for aviation.
Keywords: production savings, transport, titanium, welding.
Category of the paper: Research paper.

1. Introduction

Titanium and its alloys are difficult to weld, which is why the welding process is usually carried out in a vacuum chamber. This is an expensive technological process, which is why this article aims to check the possibility of welding a titanium alloy using the TIG method, which is 10 times cheaper. This is important from the point of view of production management. It translates into additional benefits related to environmental protection. Titanium has two allotropic varieties (alpha hcp and beta bcc), thus titanium alloys are divided into single-phase (alpha), two-phase (alpha + beta) and single-phase beta (Yee et al., 2023). Alpha alloys (α) are treated as rather well weldable. A representative of this material group may be the Ti-5Al-2.5Sn alloy, which was discussed in this article. Alpha alloys are easy to weld because they have a stable one phase microstructure and do not tend to become brittle after welding (Jaewson et al., 2011; Darabi et al., 2016). Two-phase alpha-beta titanium alloys (α+β) are rather trearted as moderately well weldable. A representative of this material group may be the Ti-6Al-4V. That alloy requires temperature control and also high quality and cleanliness protective atmosphere during welding. Beta alloys (β) are treated as materials difficult to weld. A representative of this material group may be the Ti-10V-2Fe-3Al. High content of β phase stabilizing elements causes greater tendency to brittleness. Very precise control of welding parameters is necessary. In all three groups of titanium alloys it is important to select main welding parameters, such as current, voltage and welding speed. It is important to provide an appropriate gas shield of high purity and quality, because titanium easily reacts with nitrogen and oxygen.

The paper presents the results of (Tungsten Inert Gas) welding for titanium alpha alloy Ti-5Al-2.5Sn. That alloy has good properties, high strength and good corrosion resistance, making it an interesting material for aviation application (Golański et al., 2018, pp. 53-63; Skowrońska et al., 2017, pp. 104-111). The use of high purity gases argon or helium (at least 99.995%) is necessary to avoid impurities. Helium is rather used as an additive argon gas mixture because it improves arc penetration and stability (Fydrych, Łabanowski et al., 2013; Shwachko et al., 2000). The titanium sheets should be perfectly clean before welding (Rehman, et al., 2021). Titanium alpha alloys welding requires low current because the material heats up very quickly (Faraji et al., 2021). Welding with to low speed also may result in excessive heating (Li et al., 2023). Properly selected welding speed is a very important parameter, because it allows to obtain a proper smooth weld (Piao et al., 2023).

2. Materials

For titanium alloy Ti-5Al-2.5Sn weldin with the TIG (Tungsten Inert Gas) method, two various rods (AWS A5.16: ERTi-5 based Ti-5Al-2.5Sn and rod ERTi-2 based on pur Titanium). The rod diameter was 2 mm. The main direction of research was the modification of shielding gas mixtures in the TIG process containing Ar and He. A thickness of welded sheets was 2 mm of the element in tubular form. Table 1 presents the mechanical properties of Ti-5Al-2.5Sn alloy.

Table 1.
Tensile strength of tested material

Ti alloy	YS, MPa	UTS, MPa
Ti-5Al-2.5Sn	730	820

The mechanical properties correspond with proper chemical composition (Table 2). These good mechanical properties of the alloy are the result of the chemical composition, which affects the structure of the alpha alloy. The alpha phase is responsible for good plastic properties, and the lower tensile strength than beta phase of Ti alloy.

Table 2.
Chemical composition of tested grades of alloy

Ti alloy	Al, %	Sn, %	Fe, %	O, %	N, %	C, %	Ti, %
Ti-5Al-2.5Sn	5.1	2.5	0.14	0.02	0.04	0.05	bal

The main alloying elements in alpha phase of Ti alloy are Al and Sn, which is consistent with the symbol of the material.

It was decided to realize TIG welding without chamfering. The connection was in the form of a pipe 300 mm long and 100 mm in diameter. The welded pipe was covered on both sides with a plug with 15 mm diameter holes (one hole for the shielding gas inlet, the other hole for the shielding gas outlet). A shielding gas with a variable flow rate flowed inside and outside the pipe. The weld was formed as single-pass. On the root side, the joint was protected by shielding gas mixture with constant flow on the level of 6 dm^3/min.

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,
- outlet shielding gas flow was varied twice: 15 dm^3/min and 17 dm^3/min.

The joints were made with a several combinations. The most important element of investigation included selecting 2 welding rods (AWS A5.16: ERTi-5 based Ti-5Al-2.5Sn and composition and rod ERTi-2 based on pure Ti) and selecting of proper 3 shielding gas mixture for TIG welding process containing:

- 97%Ar and 3% He,
- 92% Ar and 8% He,
- 88% Ar and 12% He.

The use of high purity gas is important to avoid welding incompabities. Actually helium is only used in argon gas mixture because helium has a higher thermal conductivity than Ar, which results in a higher arc temperature. In that investigation it was decided to eliminate preheating temperature, because titanium has about 1/7 the thermal conductivity of aluminum; which means it heats up quickly at the weld point but is slow to dissipate heat. Unlike steel, titanium is not susceptible to cold cracking (e.g., due to hydrogen hardening or residual stress).

3. Methods

After the TIG welding process without vacuum chamber, both non-destructive test (NDT) and destructive tests (DT) were carried out. Initially VT - visual test (using PN-EN ISO-17638 norm) war realized, than appropriate samples were made for destructive testing and the tensile strength (using PN-EN ISO 527-1 norm) and bending test (using PN-EN ISO 7438 norm) were carried out.

4. Results and discussion

The Ti-5Al-2.5Sn joints were made using two rods (AWS A5.16: ERTi-5 based Ti-5Al-2.5Sn and composition and rod ERTi-2 based on pur Titanium) and three different of shielding gas mixtures, 2 various shielding gas flow. Welding was realized without pre-heating temperature. Thus, 12 different samples were made, marked from U1 to U12 (tab. 4).

Table 4.
Samples designations

Sample	Shielding gas mixture	rod	shielding gas flow, dm^3/min
U1	97%Ar and 3% He	ERTi-5	15
U2	97%Ar and 3% He	ERTi-2	15
U3	92% Ar and 8% He	ERTi-5	15
U4	92% Ar and 8% He	ERTi-2	15
U5	88% Ar and 12% He	ERTi-5	15
U6	88% Ar and 12% He	ERTi-2	15
U7	97%Ar and 3% He	ERTi-5	17
U8	97%Ar and 3% He	ERTi-2	17
U9	92% Ar and 8% He	ERTi-5	17
U10	92% Ar and 8% He	ERTi-2	17
U11	88% Ar and 12% He	ERTi-5	17
U12	88% Ar and 12% He	ERTi-2	17

Visual tests were performed for all samples (U1-U12). Only five samples (U2, U3, U4, U6, U9) were free from welding defect (row column are marked in green), but unfortunately seven samples were prepared incorrectly (row column marked in pink). The Visual test results with comments on the observations during inspection are put in Table 5.

Table 5.
Visual test results for tested dissimilar welds

Sample	Observation
U1	Small cracking in HAZ
U2	Correct weld, defect free, correct form and dimension of HAZ
U3	Correct weld, defect free, correct form and dimension of HAZ
U4	Correct weld, defect free, correct form and dimension of HAZ
U5	Small cracking in weld from the face and root sides
U6	Correct weld, defect free, correct form and dimension of HAZ
U7	Small cracking in HAZ
U8	Small cracking in HAZ
U9	Correct weld, defect free, correct form and dimension of HAZ
U10	Small cracking in weld from the face and root sides
U11	Small cracking in weld from the face and root sides
U12	Small cracking in weld from the face and root sides

It was found that the selection of shielding gas flow and rod is less important than selection of gas mixture. The shielding gas flow should be on the level of 15 dm^3/min. Helium in small percentage stabilizes the welding arc of the TIG welding process. The next part of the research was to get a tensile strength of the joint. Only samples that tested positive in NDT tests were taken into further testing (U2, U3, U4, U6, U9). Table 7 presents the tensile strength (UTS) of the titanium Ti-5Al-2.5Sn alloy joints.

Table 7.
Tensile strength of Ti-5Al-2.5Sn alloy *joints*

Sample	UTS [MPa]
U2	629
U3	665
U4	655
U6	622
U9	607

The data from the tab. 7 prove that there is high tensile strength of all tested joints over the 600 MPa. It was noticed that the joint made of ERTi-5 rod (similar composition to Ti-5Al-2.5Sn alloy) had the best tensile strength.

As the last part of the article a bending tests was carried out to check the plastic properties of the joints. Measurements were done both from the root and from the face sides of the titanium alloy joint. A bending test was realized at room temperature. The results of bending test are demonstrated in Table 8.

Table 8.
Bending test of Ti-5Al-2.5Sn alloy *weld*

Sample	Face side	Root side
U2	No cracks	No cracks
U3	No cracks	No cracks
U4	No cracks	No cracks
U6	No cracks	No cracks
U9	No cracks	Small cracks

The bending tests coul be treted as a positive. No cracks were observed in the samples, when the shielding gas flow should be on the level of 15 dm^3/min (U2, U3, U4, U6). This correspond with good properties of the titanium alloy Ti-5Al-2.5Sn alloy joint. Small cracks were observed only in one case, when gas flow was to intensive.

5. Summary

The article presents the possibility of Ti alloy welding without using a vacuum chamber, which is an expensive technological process. The possibility of welding a titanium alloy using the classic TIG method was checked, which is several times cheaper. This is important from the point of production management due to the large savings and benefits related to environmental protection. Welding of Ti-5Al-2.5Sn alloy, used in the aviation industry, was tested. Main parameters of the TIG process were analyzed (2 various rods, 3 various gas mixtures). The correctess of the welds using destructive and non-destructive methods was rated. In the presented welding method, correct joints were obtained, which is important for economic reasons. The process of welding titanium alloys in a vacuum chamber is much more expensive, which does not translate into material benefits, because the mechanical properties of the joints made in a vacuum are at a comparable level to the tests presented in the article. The cost of welding titanium alloys in a vacuum chamber can be as much as 5-20 times higher than in a standard argon TIG process. The cost of equipment and installation for welding in a vacuum chamber requires specialized infrastructure, especially a hermetic chamber and multi-stage vacuum pump, while the standard TIG process requires only a power source, a welding head and good protection of a mixture of argon and helium.

Based on the research study it was possible to conclude paper:

1. Welding of alloy Ti-5Al-2.5Sn using only TIG method allows for process savings, because welding in vacuum chamber is at least 10 time more expensive process.
2. Welding parameters (rods and gas mixtures) should be selected with great knowledge and sensitivity.
3. The best mechanical properties of welds were obtained when:
   - the shielding gas mixture should contain 92% Ar and 8% He,
   - the shielding gas flow rate should be 15 dm^3/min,
   - rod has similar composition to the welded material.

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