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DISSIMILAR TI ALLOYS WELDING FOR THE AUTOMOTIVE AND AVIATION SECTOR

Summary. Titanium alloys have an excellent strength-to-weight ratio. Tit alloys are almost as strong as steel but are much lighter. This translates into reduced mass in means of transportation (e.g., aircraft, F1 cars, electric vehicles, and motorcycles), which translates into better fuel efficiency, speed. Titanium can withstand very high temperatures without losing its mechanical properties. As a result, it has found applications in exhaust systems, hydraulic lines, fuel systems, and structural elements exposed to extreme conditions. In the construction of means of transport, two types of titanium with different structures are mainly used (alpha titanium and alpha + beta titanium). There will certainly soon be a need to weld these two dissimilar materials together. This is a research gap. An absolute novelty is the attempt to weld dissimilar titanium alloys without using a protective vacuum chamber. The purpose of this article is to establish the correct parameters for this process.

Keywords: automotive, aviation; titanium; welding

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1. INTRODUCTION

Welding of titanium alloys in means of transport allows for the creation of precise and tight tubular connections, which is crucial, for example, in fuel or hydraulic systems [1]. The high quality of titanium prevents leaks and allows maintaining a high level of passive safety during transport. In aviation and automotive, very strict quality and safety standards apply. Titanium welding (e.g., TIG or MIG argon welding) meets these requirements. Maintaining high quality in accordance with certificates is especially important in aviation (AS9100). Titanium alloys are difficult materials to weld, but under the right conditions, very high-quality welds can be obtained [2]. In aviation, titanium tubes are welded into hydraulic systems, fuel lines, structural frame elements, and pipe joints in air conditioning and cooling systems. Titanium tubes in aviation are welded in automotive exhaust systems (e.g., in sports cars), cooling systems (e.g., in F1), and in the frames of high-end motorcycles or bicycles [3-4]. Titanium alloys are recommended for demanding connections, especially in the aviation and automotive industries for pressure applications. Typical applications include the aviation industry and pressure vessels with components that operate at elevated temperatures (up to approx. 400–450°C). The dissimilar welded joint between the Ti-6Al-4V titanium alloy and the Ti-5Al-2.5Sn alloy can be used in advanced aircraft and automotive structures, where a combination of different mechanical properties and resistance to environmental conditions is required [5-6]. An example of an application is titanium pipes for hydraulic, or fuel or air conditioning systems. Ti-5Al-2.5Sn is an alloy with very good weldability, corrosion resistance, and stable properties at elevated temperatures - ideal for thin-walled-pipes and pipes. Ti-6Al-4V is a more durable structural alloy, used e.g., in fasteners, flanges, connectors or brackets. In a welded joint, a pipe made of Ti-5Al-2.5Sn with a fastener or a flange made of Ti-6Al-4V forms a lightweight, durable and temperature and corrosion-resistant system. In the automotive industry, an example of the use of a dissimilar connector would be the exhaust systems in sports cars, where titanium exhaust systems are used to reduce weight and improve resistance to high temperatures [7].

Welding of titanium alloys is difficult and is usually carried out in a vacuum chamber, which makes the technology of joining titanium alloys difficult [8]. The best effects are achieved by welding with the TIG (Tungsten Inert Gas) process, less often with MIG (Metal Inert Gas). So far, titanium welding has not been attempted using micro-jet cooling, which could give great positive effects, as titanium heats up very easily. Such solutions have been tested successfully for various types of steel [9-12]. This allows for structural control and improves joint properties and quality [13-16].

Dissimilar titanium alloys can be welded using carefully selected parameters. The Ti-5Al-2.5Sn alloy with an alpha structure and the Ti-6Al-4V alloy with an alpha + beta structure were proposed as materials for testing. The dissimilar welds were prepared using several combinations of parameters. The use of purity shielding gases, such as helium or argon (at least 99.9%), is important to avoid welding defects and incompabilities [17]. Helium is mainly used as an additive in an argon gas mixture [1]. Sheets should be thoroughly cleaned before welding. When welding titanium alloys, it is recommended to use low voltage-current parameters because the material heats up quickly. There is a growing interest in the use of titanium alloys and the possibilities of welding them in the construction of aircraft and motor vehicles [18-19]. In the research it was decided not to use a vacuum chamber, which would make the welding process much cheaper and translate into ecological benefits in the sense of moving transport and the construction of means of transport towards green energy [3, 17].

2. RESEARCH MATERIALS

Ti-6Al-4V and Ti-5Al-2,5Sn are considered difficult Ti alloys to weld, due to the possibility of welding cracks [17]. Table 1 presents the mechanical properties of both materials.

Tab. 1

Ti alloys and their mechanical properties

Ti alloy	UTS, MPa	YS, MPa
Ti-5Al-2,5Sn	810	720
Ti-6Al-4V	950	810

The titanium alloy Ti-6Al-4v steel has higher tensile strength and yield point. This corresponds to the structure of both materials. The Ti-5Al-2.5Sn alloy contains only the alpha phase, while the Ti-6Al-4V alloy has the alpha phase and about 10% of the beta phase, which strengthens the material. Table 2 shows the chemical composition of both titanium alloys.

Tab. 2

Ti alloys and their chemical composition [7]

Ti alloy	Al, %	Sn, %	Fe, %	V, %	C %	Mo %	Ti, %
Ti-5Al-2,5Sn	5.1	2.5	0.14	-	0.04	-	bal
Ti-6Al-4V	5.9	-	0.19	4.1	0.02	0.6	bal

The main alloying elements in alpha Ti alloy are Al and Sn, and the main alloying elements in alpha +beta Ti are Al and V which corresponds to the symbol of the material. It was decided to check dissimilar TIG welding without chamfering. The joint had the form of a pipe 340 mm long and 76 mm in diameter. Such pipe diameters are found, for example, in aircraft air conditioning lines and in the exhaust systems of sports cars. The pipe was covered on both sides (Ti-5Al-2,5Sn from the left side and Ti-6Al-4V from the right side) with a plug with 15 mm diameter holes (first hole for the argon inlet, and the second hole for the shielding gas outlet). Argon was chosen as a shielding gas. The weld was always formed as a single pass. On the inlet side, the joint was protected by a shielding argon flow on the level of 7 dm^3/min.

The following welding parameters were set:

• the welding current was varied twice: 100 A and 110 A;
• the welding speed was varied twice: 60 mm / min and 70 mm/min;
• the outlet shielding gas flow was varied twice: 14 dm^3 / min and 16 dm^3 / min.
• the arc voltage was not varied, always 21 V.

The joints were made with several combinations. The most important element of the investigation was selecting 3 welding rods with a diameter of 1.6 mm:

1. ERTi-5 based on Ti-5Al-2.5Sn chemical composition.
2. Grade 5 based on Ti-6Al-4Sn chemical composition.
3. ERTi-2 based on pure Ti.

After the dissimilar welding, samples for mechanical tests were prepared according to the actual standards ISO 4136 and ISO 6892. The samples were cut perpendicular to the weld to assess the joint strength, and then tested for the plastic properties using a bending test.

3. RESULTS AND DISCUSSION

Welding with a rod of chemical composition similar to the Ti-6Al-4V alloy (Grade 5), and to the chemical composition of the Ti-5Al-2.5Sn rod (ERTi-2) did not give good results. The joints usually had defects and welding inconsistencies. Therefore, it was decided in this article to analyze welding using a rod (ERTi-2) with a chemical composition similar to pure titanium. In the quality testing of titanium joints, non-destructive testing (NDT) and destructive testing (DT) are used. The most recommended tests for titanium joints are penetrant testing and tensile strength testing.

After the dissimilar welding process, the non-destructive tests (NDT) were carried out, which included:

- visual test (VT) in accordance with the requirements of EN ISO 17637 standard,
- penetration test (PT) in accordance with the EN ISO 3452-1 standard (use penetrating agents compliant with AMS 2644, containing minimal amounts of halides and sulfur due to the high chemical activity of titanium). Then, some DT testing was carried out:
- tensile strength → PN-EN ISO 527-1 standard,
- bending test → PN-EN ISO 7438 standard,
- hardness test → ISO 6507-1 standard,
- macrostructure observations → ISO 17639:2022.

The results (8 cases) of the created dissimilar joints are presented in Table 3.

Tab. 3

The analysis of the non-destructive tests (welding rod ERTi-2 based on pure Ti)

Sample symbol	Outlet shielding gas flow, dm^3/min	Current, A	Speed, mm/min	Observation of the weld
L1	14	100	60	cracks in the weld and in the HAZ
L2	14	100	70	no defects in weld and HAZ
L3	14	110	60	cracks in the weld and in the HAZ
L4	14	110	70	cracks in the weld and in the HAZ
L5	16	100	60	no defects in weld and HAZ

L6	16	100	70	no defects in weld and HAZ
L7	16	110	60	cracks in the weld and in the HAZ
L8	16	110	70	no defects in weld and HAZ

Based on the data in the table, it can be stated that half of the samples were made correctly and the other half incorrectly. Initially, it can be seen that a lower welding current and a faster welding speed seem to be more beneficial. However, the most important thing seems to be the correct selection of the shielding gas flow rate, which can also have an impact on the protection of the joint against oxidation and nitriding and, additionally, can have an impact on the cooling of the joint. The pink color indicates the faulty joints, while the green color indicates the correct welds. The defects occurred in the weld and in the heat-affected zone (HAZ). In order to accurately determine the properties of the joints, destructive tests had to be performed. The next part of the research included mechanical properties. The tensile strength of the welds was tested using the INSTRON 3369. Only the joints that were made correctly (L2, L5, L6, L8) were tested (marked in green in Table 3). The results of the tensile strength (the average of 3 tests) are shown in Table 4.

Tab. 4

Tensile strength of dissimilar titanium alloy welds

Sample symbol	UTS, MPa	Elongation, %
L2	702	9,5
L5	709	9,7
L6	729	10,5
L8	716	9,1

The table data shows that a high tensile strength was obtained in all four tested cases. The highest strength was achieved for the L8 joint, which means that the linear welding energy should be limited, which corresponds to a lower current intensity and a higher welding speed. The use of a higher shielding gas flow rate is also beneficial. The UTS of dissimilar titanium joints is at the level of around 700 MPa. In order to check the plastic properties of the joints, a bending test was carried out on all dissimilar joints that had been previously tested in the tensile strength test (taken from Table 4). The test was realized in accordance with the EN ISO 5173 standard, where 5 measurements were taken for each dissimilar joint, thickness both from the root side and from the face side (Tab. 5).

No cracks were found in the weld or the HAZ (Heat-Affected-Zone) on either the face or the root sides. Small cracks were observed only in one case, when gas flow was less intensive (14 dm^3/min). The next part of the investigation corresponded with the microstructure analysis. The observations were carried out on transverse sections according to the ISO 17639:2022 standard using a Neophot microscope. The structure of the weld L8, which allowed to obtain the highest tensile strength (UTS = 729 MPa), is shown in Figure 1.

Tab. 5

Bending test of dissimilar titanium alloy welds

Sample symbol	**Face side**	**Root side**
L2	No cracks	Small cracks
L5	No cracks	No cracks
L6	No cracks	No cracks
L8	No cracks	No cracks

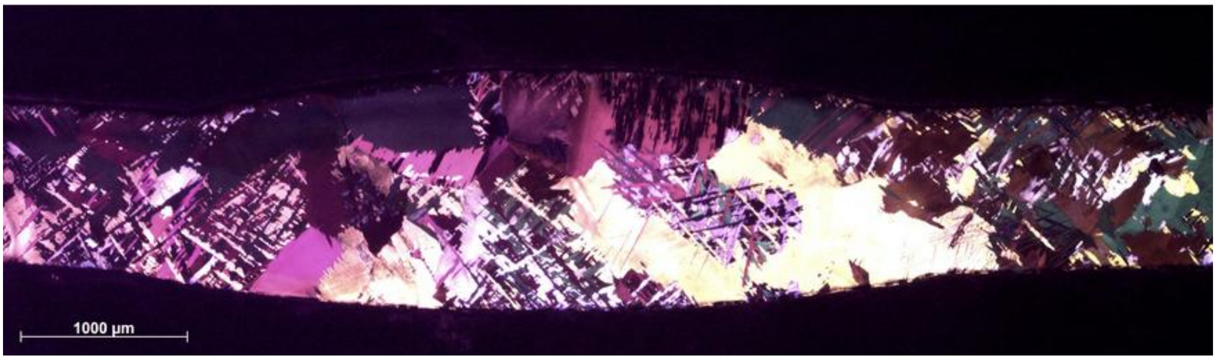

Fig. 1. The weld structure L8, Weck's reagent etching, Ti-5Al-2,5Sn on the left side and Ti-6Al-4V on the right side)

From the observation of the joint, it can be concluded that the grain is expanded in the joint in relation to the base material. Differences in grain size in different joint zones may be the cause of welding defects and inconsistencies observed in other joints (Table 5). The final stage of the tests included a hardness test. The tests were performed according to the standard ISO 6507-1.

Tab. 6

Hardness test of dissimilar titanium alloy welds

Ti-5Al-2,5Sn	HAZ	weld	HAZ	Ti-6Al-4V
217	246	306	293	297

Hardness differences were observed not only between the tested materials but also between both HAZ zones. The weld has the highest hardness. The lack of comparable hardness may also be the reason for the appearance of numerous welding defects and inconsistencies in other cases (Table 6). Detailed joint tests, especially using DT (destructive test) techniques, allow us to understand how important it is to precisely determine the most important welding parameters of titanium alloys, such as welding current intensity, welding speed, and shielding gas flow intensity. Small deviations from correctly determined parameters can translate into the appearance of welding defects and inconsistencies.

4. CONCLUSION

The welded joint between the Ti-6Al-4V titanium alloy and the Ti-5Al-2.5Sn alloy can be used in advanced aerospace and automotive structures, where a combination of different mechanical properties and resistance to environmental conditions is required. In aviation, titanium lines are used in hydraulic and fuel systems. In aircraft, titanium lines and tubes are used to transport fluids in hydraulic, fuel or air conditioning systems [18,19]. In high-performance cars, titanium exhaust systems are used to reduce weight and improve resistance to high temperatures. This article examines the possibility of welding two dissimilar titanium alloys. Ti-5Al-2.5Sn is an alloy with relatively good weldability, corrosion resistance, and stable properties at elevated temperatures - ideal for thin-walled pipes and tubes. Ti-6Al-4V is a stronger structural alloy, used e.g. in fasteners, flanges, connectors, or brackets.

An example of the use of a dissimilar titanium joint in aviation is the connection of a Ti-5Al-2.5Sn pipe to a Ti-6Al-4V fastener or flange. This results in a lightweight, strong, and temperature and corrosion resistant system. An example of the use of a dissimilar joint in automotive engineering is the exhaust system in sports cars. Titanium exhaust systems are used in high-performance cars to reduce weight and improve resistance to high temperatures. The Ti-5Al-2.5Sn alloy can be used for exhaust pipes due to its good heat resistance and weldability, while the Ti-6Al-4V alloy can be used in flanges or mounting brackets with increased mechanical strength. The article discusses a welded connection of a manifold or pipe to mounting elements that combine structural durability with heat resistance and low weight. In the research part of the article focuses on determining the most appropriate welding parameters for both titanium alloys. Initially, 3 welding rods with chemical compositions similar to each of the welded titanium alloys were tested, as well as a wire with a chemical composition similar to pure titanium. The pure titanium rod gave the best results and was therefore selected for the basic tests described in the article. It has been shown that due to differences in strength, hardness, and structure, it is not easy to determine the correct process parameters. Eight different parameter variants were tested, where the current intensity, welding speed, and the flow rate of the gas shielding the joint were changed. It was shown that the welding current should be low and the welding speed should be increased. It was determined that it is important to determine the flow rate of the shielding gas. It was shown that it is possible to make a correct pipe joint without using a vacuum chamber. This translates into large production savings and ecological benefits.

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