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The MIG Welding of Thin-Walled Tantalum Elements

Abstract: Research-related tests discussed in the article included the manual TIG welding of thin-walled elements made of tantalum, i.e. a sheet having a thickness of 0.55 mm, a tube (Ø10×1.0 mm) and a chemical equipment nozzle tip. Welding jigs were placed in a chamber filled with argon. The verification of the correctness of the welding technology developed during the tests included the welding-based filling of the crack in the girth fillet weld of the tantalum tube and the making of a repair weld in the nozzle tip.

Key words: Tantalum, TIG welding, repair welding

1. Introduction

Tantalum belongs to high-melting metals and is characterised by high corrosion resistance in the environment of aggressive acids, high-temperature creep resistance and lacking oxidation resistance [1]. In addition to applications in electronics, where it is used in the fabrication of electrolytic capacitor foils and sintered anodes (65.7 % share in entire production) and aerospace technologies (8.2 %), tantalum has also found applications (in the form of sheets, plates, bars and tubes; 2.7 %) in the production of chemical equipment (heat exchangers, liquefiers and vessels) [1]. The metal is also characterised by highly favourable technological properties and high weldability [1, 2]. However, the technological weldability of tantalum is restricted by a high melting point, relatively high thermal conductivity and high oxidability at high temperature. In terms of its physical properties, tantalum differs significantly from high-alloy steels or titanium (widely used in the fabrication of welded products) (Fig. 1–4).

Tantalum forms high-melting oxides. The melting point of Ta2O5 (i.e. 1900 °C) is lower than that of the metal itself. The specific volume of oxides is significantly greater than that of the base material. As a result, oxide layers undergo cracking and delamination, thus providing oxygen with access to the metal surface. The oxidation of tantalum starts from temperature ≥ 300 °C [7]. Being less reactive with nitrogen than with oxygen, tantalum is resistant to nitrogen up to a temperature of 450 °C. At higher temperature, tantalum also reacts with carbon and hydrogen. The above-

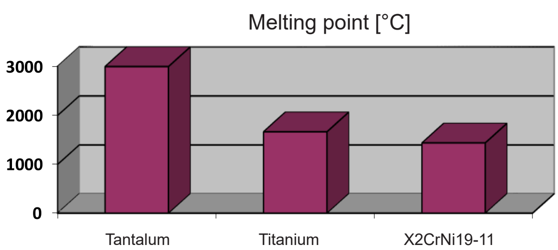

Fig. 1. Comparison of the melting point of tantalum, titanium and steel X2CrNi19-11 [1, 3–6]

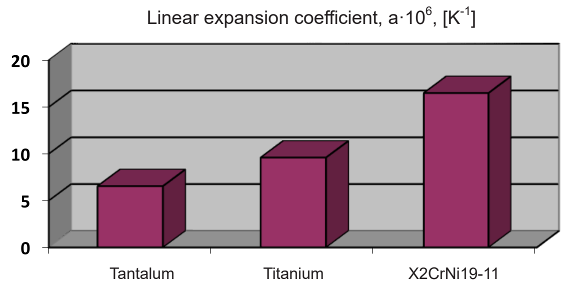

Fig. 2. Comparison of the linear expansion coefficient of tantalum, titanium and steel X2CrNi19-11 [1, 3–6]

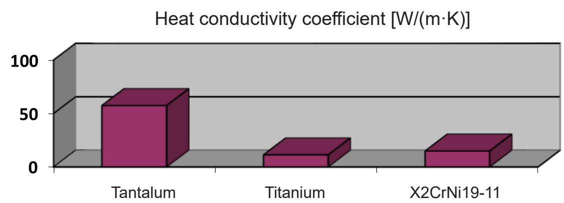

Fig. 3. Comparison of the heat conductivity coefficient of tantalum, titanium and steel X2CrNi19-11 [1, 3–6]

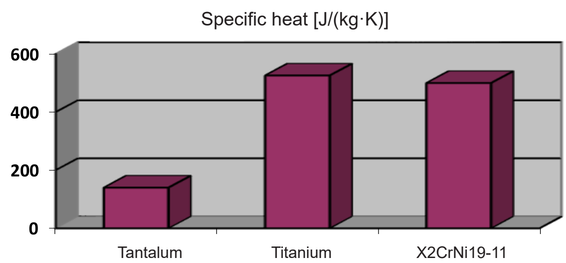

Fig. 4. Comparison of the specific heat of tantalum, titanium and steel X2CrNi19-11 [1, 3–6]

named chemical elements, as well as oxygen and nitrogen, interstitially dissolved in tantalum increase its strength, yet at the expense of reduced plasticity [8]. For this reason, in all cases of heating (and welding), tantalum must be separated from contact with air and hydrogen. Solutions proposed in reference research publications include the electron

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beam welding of tantalum in vacuum, diffusion welding in vacuum and TIG welding in chambers with a controlled atmosphere or with local gas shielding, i.e. in chambers featuring the flow of inert gas (the so-called chamber welding) [6–10]. It is also possible to use TIG welding in open space, providing appropriate gas shielding [6].

The TIG welding of metals characterised by high chemical activity and sensitive to shielding gas impurities (e.g. tantalum, titanium and zirconium) requires the use of shielding gases characterised by very high purity. In such cases it is recommended to use argon having a purity of 99.996 %, helium having a purity of 99.998 % [11] or inert mixtures of argon with helium. Because of the fact that helium is approximately 7-fold lighter than air, the flow of the former should be intense in order to properly shield the welding area. Helium provides higher arc energy than argon, which is connected with higher arc voltage in the former. The high flowing power of the helium-shielded liquid metal pool reduces the risk of weld porosity formation. In turn, argon, because of its density of 1.7836 kg/m^3, significantly higher than that of helium (0.1785 kg/m^3), provides more effective gas shielding. Because of its low specific gravity, helium is not recommended for shielding the weld root.

The gas shielding must be fully effective until the temperature of tantalum does not fall below the initial temperature of the active absorption of gases, i.e. 250 °C [6].

In publications [7, 8] it can be found that the pre-weld preparation of elements made of tantalum should be subjected to mechanical cleaning followed by chemical cleaning performed using a mixture composed of 90 % HF + 10% HNO3. Directly before welding, elements to be joined should be degreased and dehydrated using ethanol. It is recommended that, after mechanical treatment, elements made of tantalum alloys should be rinsed with acetone, etched for 30 seconds in the 55 % solution of H_2SO_4 + HF, rinsed with warm water and dried using forced warm airflow [12]. As regards the TIG welding of tantalum elements performed in a vacuum chamber it is recommended that, after welding, the joint should be left for cooling in the chamber for approximately 5 minutes.

The welding of technical tantalum and some of its alloys containing Nb, V and W, properly shielded against atmospheric gases (O_2 < 0.003 % and N_2 < 0.01 % in the shielding gas), makes it possible to obtain the high plasticity and strength of joints, comparable with those of the base material [7].

Only a few scientific publications provide exemplary parameters used in the manual (standard arc) TIG butt welding of joints in tantalum, the thickness of which is restricted within the range of 0.6 mm to 1.5 mm [6, 7, 13]. Depending in the source, the aforesaid parameters differ significantly, e.g. as regards joints having a thickness of 1.5 mm [6, 7]. Tantalum can also be welded using the pulsed-arc TIG method [13, 14].

The repeated effect of the welding thermal cycle triggers the grown of grains in the weld and in the heat affected zone (HAZ), which, to some extent, reduces the plasticity of welded joints made of tantalum and induces their brittleness [15].

Publication [6] presents examples of repair welding of impact-triggered cracks in an element made of a 1.2 mm thick tantalum sheet. The solution proposed in the study involved the making of flange welds or the melting of wire in the V-shaped weld groove. Repair welding-induced problems included the formation of porosity and solidification cracks. Available reference publications did not contain any information concerning the repair welding of elements made of tantalum.

2. Objective and scope of tests

The tests discussed in the article aimed to develop a technology enabling the TIG method-based repair welding of tantalum elements of chemical equipment and the repair welding of a crack located in a T-joint. The scope of technological tests included the making of longitudinal and girth butt welds of a tube as well as the making of a fillet weld in a T-joint and in an angle joint.

3. Technological tests

3.1. Materials

The base materials used in the tests were sheets having a thickness of 0.55 mm and tubes (Ø10×1 mm). The welding process was performed using tantalum wire grade R05200 (unalloyed vacuum-melted tantalum, min. 99.95 % Ta in accordance with ASTM B365-12 [16]) having a diameter of 1.6 mm. The chemical composition of the wire is presented in Table 1, whereas its mechanical properties are presented in Table 2.

The welding process involved the use of a tungsten electrode (ISO 6848–WTh 20) having a diameter of 2.4 mm, shielding gas (argon EN ISO 14175–I1 (purity: 99.996 %)) and the mixture of argon and helium (EN ISO 14175–I3–ArHe–50).

3.2. Technological tests concerning the welding of tantalum sheets

A series of technological welding tests revealed that the proper formation of the weld and the obtainment of satisfactory gas shielding were ensured by shielding the weld face and root using special equipment. The butt joints made in a 0.55 mm thick sheet were welded using a steel strip with a groove for supplying the gas shielding to the weld root and a cuboidal gas tip (additionally shielding the welding area from the weld face) placed on the TIG torch.

Table 1. Chemical composition of the tantalum wire [16]

Contents of chemical elements, [mass %], gas contents [ppm]							
Ta	**Nb**	**W**	**Fe**	**Co**	**Hf**	**Mo**	**Ni**
Shielding	0.0033	0.0111	0.0006	< 0.0001	< 0.0001	0.0026	0.0006
Ti	**Si**	**C**	**Zr**	**Mn**	**O**	**H**	**N**
0.0002	< 0.0001	0.0036	< 0.0001	< 0.0001	0.0096	0.0004	0.0006

Table 2. Mechanical properties of the tantalum wire [17]

Yield point, $R_{0,2}$ [MPa]	Tensile strength, R_m [MPa]	Elongation, A_{min} [%]
114	227	44

Table 3. Welding process parameters

Welding current [A]	55
Arc voltage [V]	11–12
Welding rate [cm/min]	8
Shielding gas	EN ISO 14175–I3–ArHe–50
Flow rate of the gas shielding the arc [l/min]	9
Flow rate of the gas shielding the tip [l/min]	8
Flow rate of the gas (argon) shielding the weld root [l/min]	12

The length of the tip from the torch axis amounted to 110 mm. The welding process parameters and conditions are presented in Table 3.

The performance of penetration was easier when the Ar+He mixture, rather than argon, was used as the shielding gas. In addition, the aforesaid approach offered the better visibility of a metal drop added during the process. The weld face was shiny, metallic and smooth and so was the weld root, which indicated the proper gas shielding of the weld metal. Visual tests did not reveal the presence of cracks or porosity of the test joints.

3.3. Technological welding tests of a tantalum tube

Longitudinal butt welded joints of a tantalum tube were made after square butt weld preparation, (Fig. 5) performed using a 0.8 mm thick steel blade, opposite the longitudinal production joint of the tube.

Fig. 5. Tube (Ø10×1 mm) after square butt weld preparation

The TIG welding process was performed in two variants. The first variant involved the additional flow of argon from the weld face side performed using a ceramic nozzle (JUMBO TIG no. 12) with a gas lens; gas nozzle outlet diameter being 19 mm (see the weld in Fig. 6, segment A). In turn, the second variant involved the use of a cuboidal gas tip

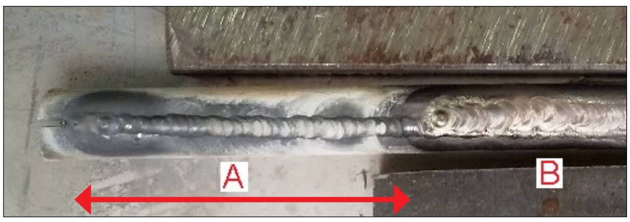

Fig. 6. Segment A of the joint made using the insufficient gas shielding of the weld metal and segment B made using the improved gas shielding of the weld face

(chamber) placed on the TIG torch. The tip was provided with a copper tube (located inside the tip) featuring holes providing the addition gas shielding of the weld face (Fig. 6, segment B). The welding parameters and conditions are presented in Table 4.

Table 4. Parameters used in the longitudinal butt welding of the tantalum tube

Welding current [A]	70
Arc voltage [V]	11.5–12.5
Welding rate	6.5
Flow rate of the gas shielding the arc, TIG torch [l/min]	9
Flow rate of the gas shielding the arc, JUMBO TIG nozzle [l/min]	7
Flow rate of the gas shielding the tip [l/min]	8
Flow rate of the gas (argon) shielding the weld root [l/min]	8

The subsequent stage involved the making of a longitudinal joint of the tube using insufficient gas shielding. The weld face was oxidised and covered with a relatively thick layer of oxides. The welding process was followed by the crushing of the tube from its diameter of 10 mm to that of 8 mm. During the crush test, the test joint underwent cracking. The cross-section of the tube after the crush test is presented in Fig. 7. The longitudinal production joint of the tube is designated as joint 3P, whereas the test joint with the visible crack is designated as joint 3A.

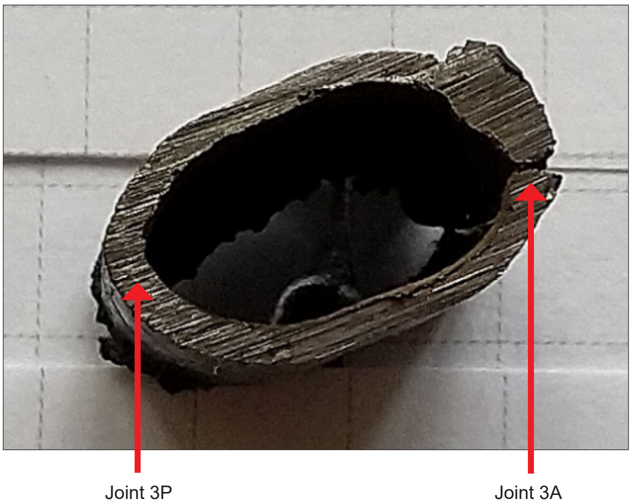

Fig. 7. Tube cross-section after the crush test; visible crack of joint 3A

Joints 3P and 3A after the crush test are presented in Figures 8–10. Visual tests involving the tube welded (by the producer) using the TIG method (joint 3P, Fig. 7) did not reveal the presence of cracks. The crack in the test butt welded joint was initiated in the heat affected zone (HAZ) and propagated in the weld (Fig. 9 and 10). The crush test result indicated the brittleness of the insufficiently gas-shielded tantalum joint.

Joints 3A and 3P were also subjected to microscopic metallographic tests aimed to detect the presence of micro-cracks (if any). The microstructure of the test joints was revealed through chemical etching in a reagent composed of nitric acid (HNO_3) and hydrofluoric acid (HF), mixed

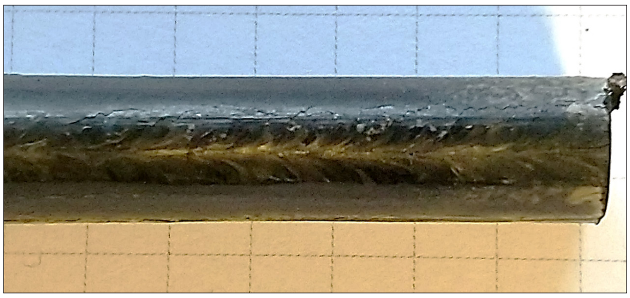

Fig. 8. Weld face of the TIG butt welded joint of the tube (welded by the producer) after the crush test

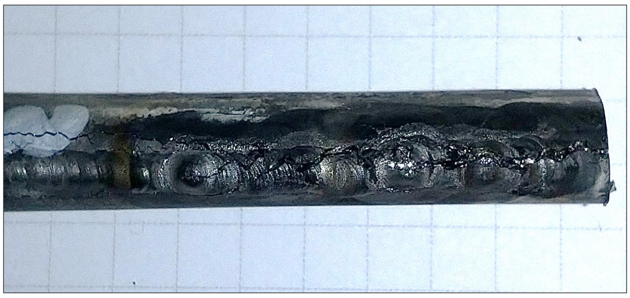

Fig. 9. Crack in the HAZ and in the weld of test joint 3A, in accordance with Fig. 7

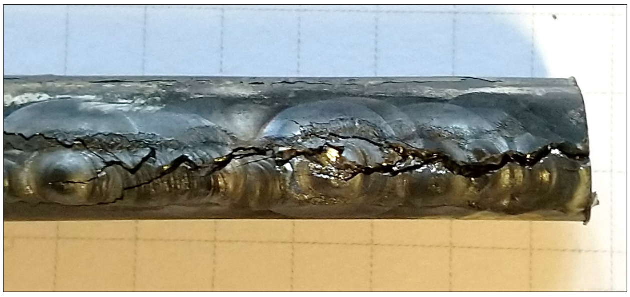

Fig. 10. Crack in the weld of test joint 3A after the crush test

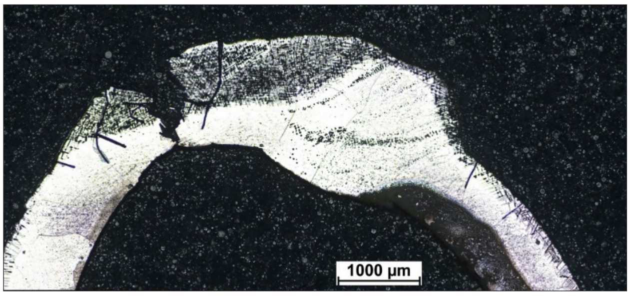

Fig. 11. Main view of welded joint 3A with the crush-test triggered crack

in a proportion of 1:1. The etching time amounted to 10 minutes. The macroscopic metallographic tests were performed using an Eclipse MA200 light microscope (Nikon) and an NIS Elements-AR software programme (Nikon). The joint 3A-related test results are presented in Figures 11–12, whereas the joint 3P-related test results are presented in Figures 13–14.

The technological welding tests also included the determination of conditions concerning the girth welding of the tube (Ø10×1.0 mm) (see Table 5). The pre-weld preparation of the tubes involved cutting with a metal-cutting handsaw, followed by the degreasing of the test elements with ethanol. The tubes subjected to welding were put together without a gap. The gas mixture shielding the arc was EN ISO 14175–I3–ArHe–50. The weld face and the weld root were shiny, which indicated the proper gas shielding of the welding area. Full penetration was obtained around the entire circumference (Fig. 15).

The macrostructure of the girth joint in zones A and B, in accordance with Fig. 15, is presented in Figures 16 and 17 respectively. The macroscopic tests of zones A and B of the girth joint did not reveal the presence of cracks.

3.4. Technological welding tests concerning the angle joint of the nozzle tip

Subsequent technological tests involved the welding of an angle joint of the nozzle tip (Ø52 mm, height of 120 mm) in a dedicated device with a closed chamber (internal diameter of 80 mm, height of 130 mm) and a shielding gas connection. The upper cover of the device had a hole providing access (of the TIG torch and filler metal) to the welding zone. Before welding, the chamber was thoroughly rinsed with argon. The flow rate (adjusted gradually) of argon fed (during welding) to the chamber from beneath was restricted within the range of 2 l/min to 5 l/min. Because of the limited access to the welding zone, the girth joint of the nozzle tip was made segmentally. Technological welding process parameters used during the making of the joint (Ø30 mm) are presented in Table 6. Before welding, the elements were degreased with ethanol. The gas mixture shielding the weld face was EN ISO 14175–I3–ArHe–50.

The weld face was shiny, which indicated the proper gas shielding of the welding zone.

3.5. Repair welding of the tantalum tip of the spray nozzle

The verification of the welding technology developed by the Authors involved the filling of the crack of the injector tantalum tube as well as the making of a repair weld of the tantalum nozzle (and the performance of related tests). The repair welding of the cracked fillet weld (Fig. 18) was

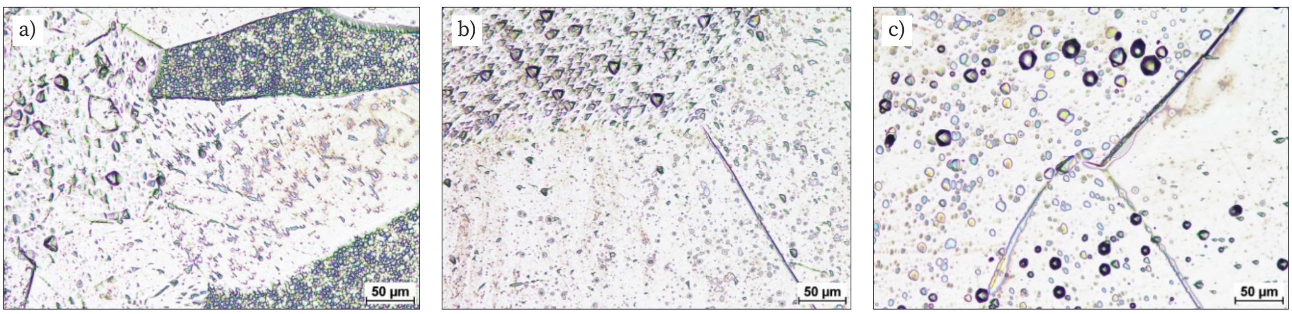

Fig. 12. Microstructure of welded joint 3A: a) base material, b) HAZ and c) weld

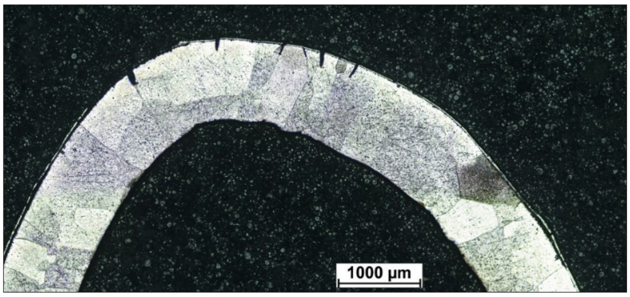

Fig. 13. Main view of production joint 3P after the crush test

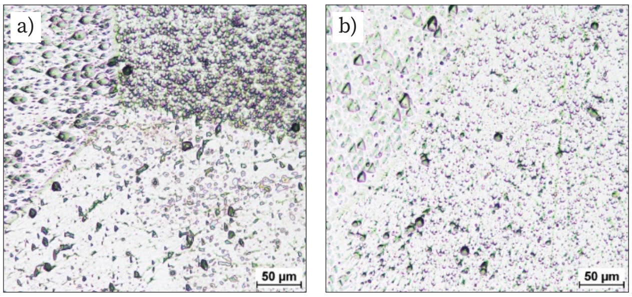

Fig. 14. Microstructure of welded joint 3P: a) HAZ and b) weld

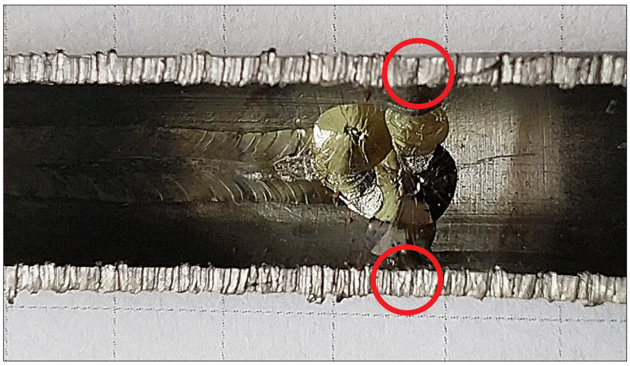

Fig. 15. Weld root of the girth joint of the tube with areas (marked) subjected to macroscopic metallographic tests (upper circle – zone A and lower circle – zone B)

Table 5. Parameters used in the girth butt welding of the tantalum tube

Welding current [A]	80
Arc voltage [V]	11–12
Welding rate [cm/min]	7.5
Flow rate of the gas shielding the arc, TIG torch [l/min]	10
Flow rate of the gas shielding the arc, JUMBO TIG nozzle [l/min]	10
Flow rate of the gas shielding the tip [l/min]	8
Flow rate of the gas (argon) shielding the weld root [l/min]	8

Table 6. Parameters used during the welding of the angle joint of the tantalum nozzle tip

Welding current [A]	160
Arc voltage [V]	14–15
Welding rate [cm/min]	6
Flow rate of the gas shielding the arc, TIG torch [l/min]	10
Flow rate of the gas shielding the arc, JUMBO TIG nozzle [l/min]	10

Table 7. Parameters used in the repair welding of the tantalum tip of the spray nozzle

Welding current [A]	125
Arc voltage[V]	14–15
Welding rate [cm/min]	6
Gas shielding the weld face	argon
Flow rate of the gas shielding the arc, TIG torch [l/min]	10
Flow rate of argon fed to the tube [l/min]	10
Flow rate of argon fed to the chamber – rinsing [l/min]	3
Flow rate of argon fed to the chamber – during welding [l/min]	10

performed in a device featuring a chamber providing the gas shielding of the welding area (Fig. 19).

The technological parameters of the repair welding of the tube crack are presented in Table 7.

The proper quality of the repair welding of the injector tube crack was confirmed by visual tests and a bubble method-based leak test. The performance of the above-named test involved the making of connectors feeding compressed air and plates plugging injector holes (with rubber gaskets). The leak test was performed under a pressure of 0.4 MPa. The test joint was covered with a solution of foam-producing substance (liquid detector). The test result was positive as no leak was detected in the welded joint area of the tube. The tests concerning the girth T-joint with the

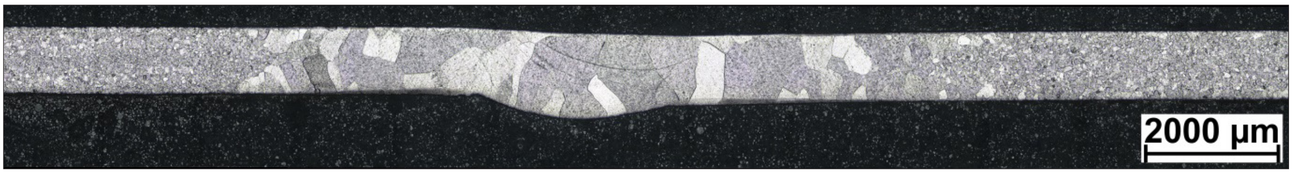

Fig. 16. Macrostructure of the girth butt welded joint – zone A

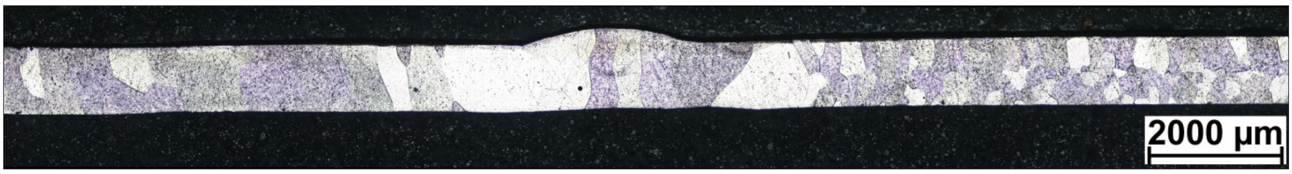

Fig. 17. Macrostructure of the girth butt welded joint – zone B

Fig. 18. Weld with the crack

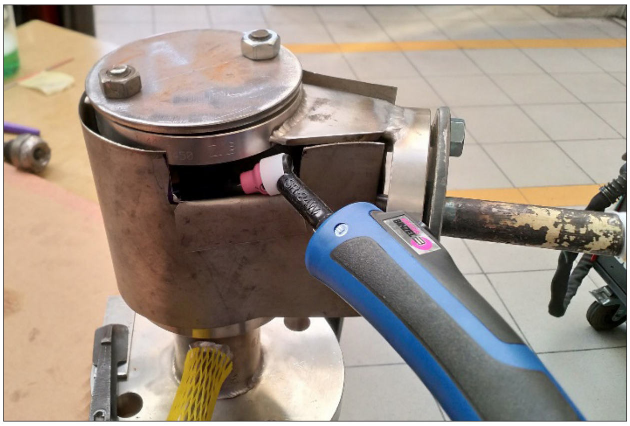

Fig. 19. Device used during the repair welding of the injector tube (during assembly)

fillet weld of the nozzle tip subjected to repair welding (in the chamber filled with shielding gas) also produced positive results.

4. Conclusions

The technological test concerning the TIG welding of thin-walled elements made of tantalum justified the formulation of the following conclusions:

1. The welding technology developed within the research work discussed in the article can be used for making welded joints of elements made of 0.55 mm thick sheets and tubes (Ø10×1 mm). The obtainment of good-quality joints requires the use of appropriate equipment (chamber) providing the gas shielding of the weld face and weld root as well as the application of previously defined technological parameters.
2. The crush test of the tantalum tube with the insufficiently gas-shielded welded joint revealed the brittleness of the latter.
3. The macro and microscopic tests of the properly gas-shielded joint of the tantalum tube (Ø10×1 mm) did not reveal the presence of cracks and microcracks.
4. The welding technology involving the use of the chamber filled with argon enabled the performance of the proper repair welding of the injector tube crack and of the spray nozzle tantalum tip.

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