A R C H I V E S O F M E T A L L U R G Y A N D M A T E R I A L S
Volume 57 2012 Issue 1
DOI: 10.2478/v10172-011-0150-5

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PECULIARITIES OF A-TIG WELDING OF TITANIUM AND ITS ALLOYS

OSOBLIWOŚCI SPAWANIA ŁUKOWEGO METODĄ A-TIG TYTANU I JEGO STOPÓW

The paper contains the findings of investigation of the impact of activating flux and selected fluorides on A-TIG welding of Grade 2 titanium. The paper also presents the dimensions and macrostructure of welds and describes welded joints produced with BC-Ti activating flux as well as the mechanical properties such as strength, impact energy and hardness of specific weld zones. In addition, the article contains information about performed bend tests and results of macrostructure investigation.
Keywords: A-TIG welding, activating flux, welded joint, structure, mechanical properties, titanium

Przedstawiono wyniki badań wpływu topnika aktywującego oraz wybranych fluorków na proces spawania metodą A-TIG tytanu w gat. Grade 2 oraz wymiary i makrostrukturę spoin. Wykonano ponadto złącza spawane z zastosowaniem topnika aktywującego BC-Ti oraz określono ich własności mechaniczne, w tym wytrzymałość, pracę łamania oraz twardość poszczególnych stref złącza, jak również przeprowadzono próby gięcia i zbadano makrostrukturę.

1. Introduction

Titanium and its alloys belong to the group of materials whose application in various industries is increasing [1]. One of the decisive factors responsible for the dynamics of the aforesaid growth lies in the improvement of methods used for joining (e.g. welding) of specific structural elements. At present, the basic methods applied for welding titanium and its alloys include tungsten inert gas welding (TIG), metal inert gas welding (MIG), plasma arc welding (PAW), electron beam welding (EBW) and laser beam welding (LBW). Each of the aforementioned methods has its advantages and disadvantages, which entails the necessity of constant improvement. One of such solutions is A-TIG welding, which is a variety of traditional TIG welding incorporating the use of activating flux deposited on the surfaces of the edges of joined elements. The effect of the flux consists in narrowing the welding arc, concentrating energy on a small area and changing the surface tension of liquid metal in the weld pool, which, in consequence, increases the penetration depth, decreases the width of a weld and increases welding efficiency. The text below presents the findings of investigation of peculiarities of A-TIG welding of titanium as well as provides characteristics of joints produced by means of this method.

2. A-TIG welding of titanium and its alloys – literature survey

At the initial stage of research on fluxes for TIG welding of titanium it was possible to observe that the aforesaid fluxes influence arc burning stabilisation, protect welds against harmful effect of air as well as have an effect on the metallurgical treatment of the weld pool, affect weld porosity etc. In addition, during the said investigation it was ascertained that the use of fluxes for TIG welding has a positive effect not only on the metallurgy of the welding process but also results in an increase and stability of the penetration depth and reduces the weld width [2]. This positive effect was attributed to the fact, that, just as is the case with submerged arc welding, the presence of liquid flux on the surface of the weld pool limits the size of the heating spot and eliminates the phenomenon of the so-called "wandering arc", which in turn, helps concentrate the heat flow on a very small area. Further research proved that the above thesis only partly reflects the actual mechanism of the impact of flux during A-TIG welding. The aforesaid finding, however, did not contradict the fact of an increased penetration depth or reduction of welding-related strains not only of titanium but of many other structural materials as well.

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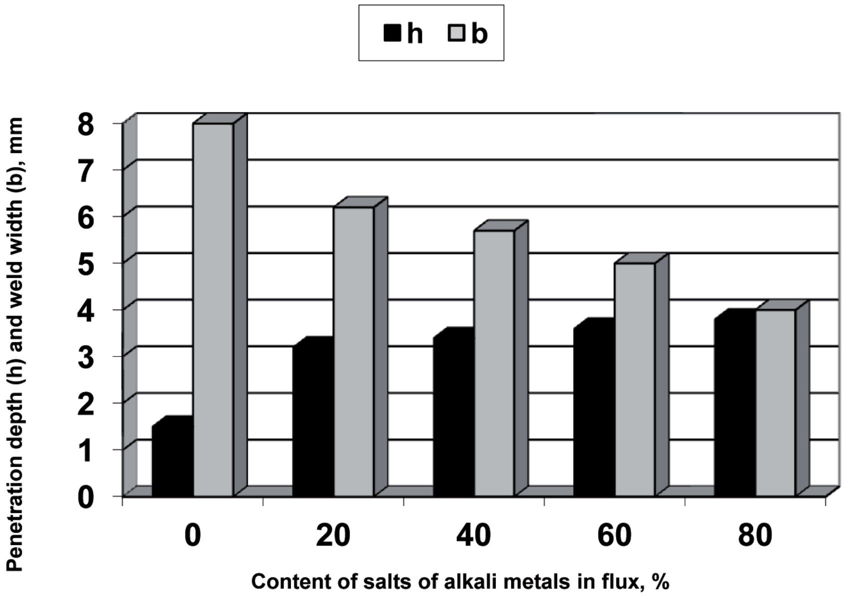

Fig. 1. Relation between dimensions of welds produced with TIG method during welding of Grade BT 15 titanium-based alloy and content of salts of alkali metals in flux (I = 100 A; U = 9 V; V_w = 15 m/h) [2]

The authors of this publication [2] determined that the increase in penetration depth accompanying TIG welding of titanium alloys could be attributed to the application of the salts of alkali metals i.e. fluorides and chlorides. As can be seen in the diagram presented in Fig. 1, 80% content of the salts of alkali metals in the flux more than doubles the penetration depth and doubly decreases the weld width during TIG welding of Grade BT 15 titanium-based alloy if compared to welding with flux void of the aforesaid salts.

The research work [3] resulted in a conclusion that the use of flux during TIG welding of OT4 titanium alloy enables obtaining the same penetration depth as in case of welding without flux, yet in the latter case the process requires almost twice as high current intensity. In such a process as described above, the linear energy is, on the average, reduced by 35÷40%. The said decrease of current intensity and linear energy of welding as well as the reduction of the weld width related to the use of TIG welding with flux favours the reduction of HAZ width. Moreover, in most cases, the welds produced by means of A-TIG method have similar dimensions both in the face and root areas (Fig. 2). The application of flux in TIG welding of titanium alloys results in the reduction of weld porosity as well as leads to refinement of α' – structure inside the grains. In turn, an increase in cooling speed favours the refinement of the primary β–grains, which increases the plasticity of the welded joints produced from OT4 and BT6C alloys.

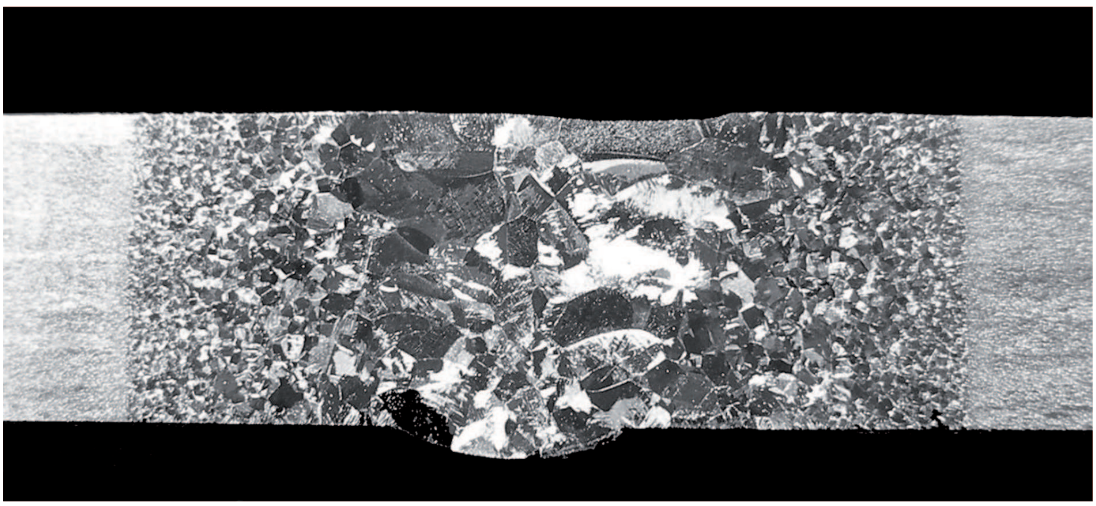

Fig. 2. Shape of butt weld of 5 mm-thick Grade 2 titanium sheets produced by means of A-TIG method with BC-Ti activating flux

The investigation of A-TIG welding of $^1/_4$ inch-thick (approx. 6 mm) CP-type (*commercially pure*) titanium sheets as well as of Ti-6Al-4V titanium alloy proved [4] that during joining of Ti-6-4 alloy it is possible to observe an increase in the penetration depth if compared to that observed in flux-free TIG welding. It was also determined that mechanical properties of joints obtained by means of both methods are similar and that the content of oxygen and hydrogen in the weld is slightly higher if the flux has been applied (Table 1). An increase in the penetration depth was observed also in the research works [5, 6].

TABLE 1
Mechanical properties and chemical composition of CP and Ti-6-4 welded joints[4]

Parametr	Sample denotation			
	CP-59	CP-59B with flux	Ti-6-4-59	Ti-6-4-59B with flux
$R_{0,2}$, MPa / YS, ksi	372 / 54	372 / 54	883 / 128	848 / 123
R_m, MPa / UTS, ksi	476 / 69	469 / 68	1014 / 147	1007 / 146
Elongation, %	28	37	7	8
C	0.006	0.005	0.028	0.011
N	0.003	0.002	0.005	0.011
O	0.016	0.16	0,23	0.22
H	0.0014	0.0017	0.0056	0.0075
Fe	0.06	0.06	0.17	0.2
Al	<0.02	<0.02	6.33	6.47
V	<0.02	<0.02	4.18	4.25
Zr	<0.02	<0.02	<0.02	<0.02
Mn	<0.02	<0.02	<0.02	<0.02
Cr	0.02	0.02	0.02	0.02
Ni	0.02	0.02	<0.02	<0.02
Cu	<0.02	<0.02	<0.02	<0.02
Mo	<0.02	<0.02	<0.02	<0.02
Sn	<0.02	<0.02	<0.02	<0.02
Si	<0.02	<0.02	<0.02	<0.02
Ti	Bal.	Bal.	Bal.	Bal.

The research on A-TIG welding of Ti-6Al-4V titanium alloy proved that welds produced by means of the traditional TIG method were uniform and smooth but, at the same time, wider and shallower than those manufactured with the A-TIG method [7]. It was also ascertained that the welds made with the A-TIG method are characterised by a higher proportion of height to width and bigger penetration depth (by approx. 20%) if compared to those produced with traditional TIG welding. The examination performed with an optical microscope did not reveal more significant differences in the microstructure of the welds produced by means of both methods. In addition, it was determined that, due to a higher cooling speed, the material of the weld produced with lower current contains more martensite, which in turn, results in obtaining higher hardness values than in case of welding with higher current.

3. Results of investigating impact of fluorides unary fluxes on dimensions of welds produced with A-TIG method

The tests concerning the impact of activating fluxes on the shape and dimensions of welds incorporated the use of Grade 2 CP titanium sheet acc. ASTM B 265 of the following dimensions: 300×200×7.4 mm. During the tests, welds were produced by means of the traditional TIG method as well as applying the A-TIG method with BC-Ti flux and single component (unary) fluxes in the form of fluorides: AlF_3, CaF_2, MgF_2, NaF using the welding energy source KEMPPI 500. In all of the cases, welding parameters were the same i.e. welding current of 200 A and the speed of welding clamp travel of 15 cm/min. The results of measurements of the dimensions of welds and their macrostructure are presented in Figures 3 and 4.

The results of examination concerning the dimensions of the welds produced without filler metal on the surface of Grade 2 titanium sheet reveal that the application of all the fluorides used in the tests increases the penetration depth, if compared to traditional TIG welding (Fig. 3). The most significant increase (76%) accompanies the use of magnesium fluoride (MgF_2). Slightly lower i.e. 50% increase can be observed in case of the application of calcium fluoride (CaF_2) and BC-Ti flux worked out and produced by Institute of Welding in Gliwice. The remaining fluorides used for the tests i.e. sodium fluoride (NaF) and aluminium fluoride (AlF_3) showed no significant impact on the penetration depth. The results presented above differ slightly to those found in other reference sources [8] considering aluminium fluoride, apart from magnesium fluoride, to be responsible for the highest increase in the penetration depth.

Equally interesting are the results concerning the measurements of the HAZ widths both on the face and root sides. It was ascertained that the HAZ width on the face side does not change proportionally to the width of the face of the welds; it was also stated the differences related to the application of unary activating fluxes are not as significant as in case of the differences between the width of the welds. The face width measurement results were situated within 6.8÷12.0mm range, whereas the HAZ width values - within 14.0÷17.1 mm range. As can be seen from the foregoing, the differences in the width of the welds slightly exceeded 75%, whereas the differences in the HAZ width amounted to mere 22%. Even smaller were the differences between HAZ widths on the root side i.e. max. 10%.

The macrostructure of the welds produced on Grade 2 titanium sheet reveals a high grain growth tendency of this material both as regards the weld and HAZ (Fig. 4); the aforesaid growth being triggered by heating, particularly over 882°C (in phase β area). Low heat conductivity of titanium is responsible for prolonging the time at which the weld and areas near the weld remain exposed to higher temperatures, which in turn favours increasing of grain sizes. It was also detected that the sizes of grains during A-TIG welding are bigger (approx. 90%) than in case of traditional TIG welding; this phenomenon can be attributed to more intense overheating of the metal of the welds obtained with A-TIG welding resulting from their specific i.e. deep and narrow shape.

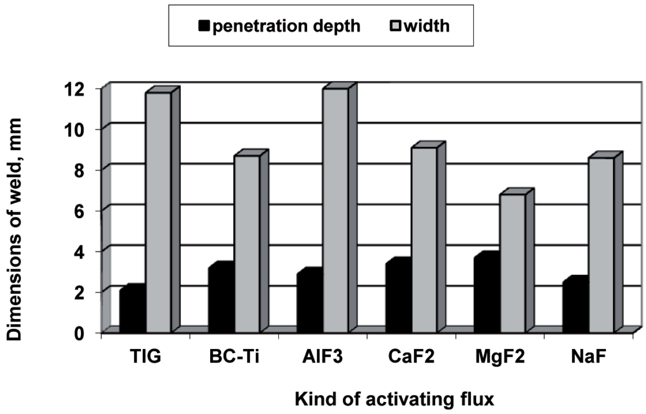

Fig. 3. Impact of type and content of activating flux on penetration depth and width of faces of welds produced with TIG and A-TIG methods on Grade 2 titanium sheet

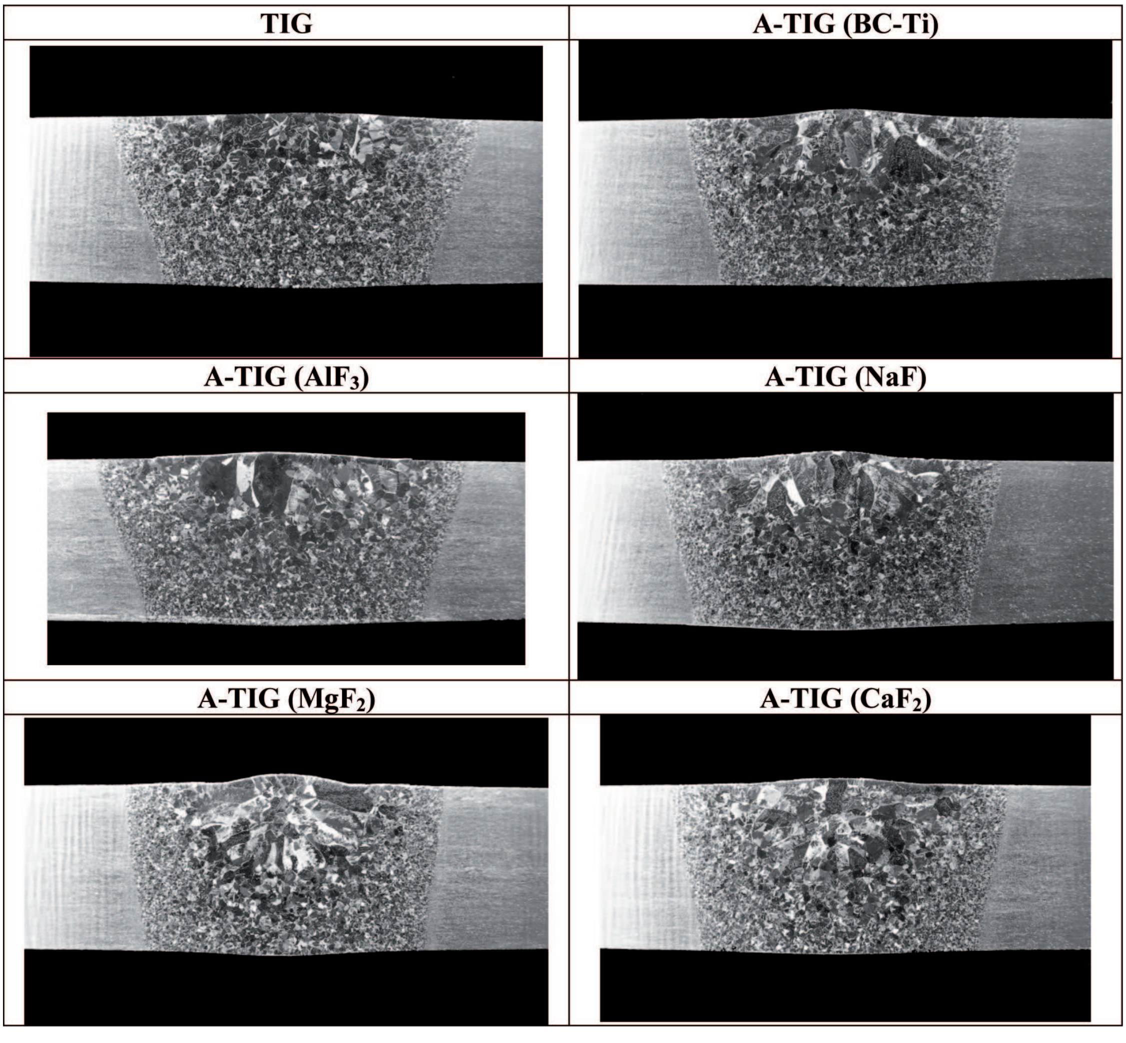

Fig. 4. Macrostructure of welds produced on 7.4 mm-thick Grade 2 titanium sheet by means of TIG and A-TIG methods with BC-Ti activating flux and fluorides: AlF_3, NaF, MgF_2 and CaF_2 (Kroll's reagent)

The analysis of the dimensions of the experimental welds and the absence of strains on the test titanium sheet after welding reveal that the use of activating fluxes for welding of pure titanium should be aimed not so much at the reduction or elimination of welding-related strains but, first of all, at increasing the penetration depth and eliminating the necessity of V-bevelling of thick titanium sheet, which, in consequence, would decrease labour consumption and the cost of production of welded joints. Therefore, the objective related to the application of fluxes in welding of pure titanium is slightly different than that related to welding of high-alloy steels or nickel alloys, where the use of activating fluxes not only increases the penetration depth but also significantly reduces welding strains [9].

4. Results of investigation of properties of welded joints produced by means of A-TIG method

The investigation of mechanical properties of butt welded joints manufactured with the A-TIG method incorporated the use of Grade 2 CP titanium sheet (300×200×5 mm) and BC-Ti activating flux. For comparative purposes it was also necessary to produce test joints by means of the traditional TIG method. The joints were I-shaped, with no spacing. In both cases no filler metal was used and the same welding parameters were applied i.e. welding current of 120 A and the speed of welding clamp travel of 15 cm/min. The test joint was subject to radiographic examination and sampled for material used in strength tests and bend tests. The macrostructure of the test welded joint is presented in Figure 5 and the results of the investigation concerning mechanical properties are shown in Tables 2 and 3.

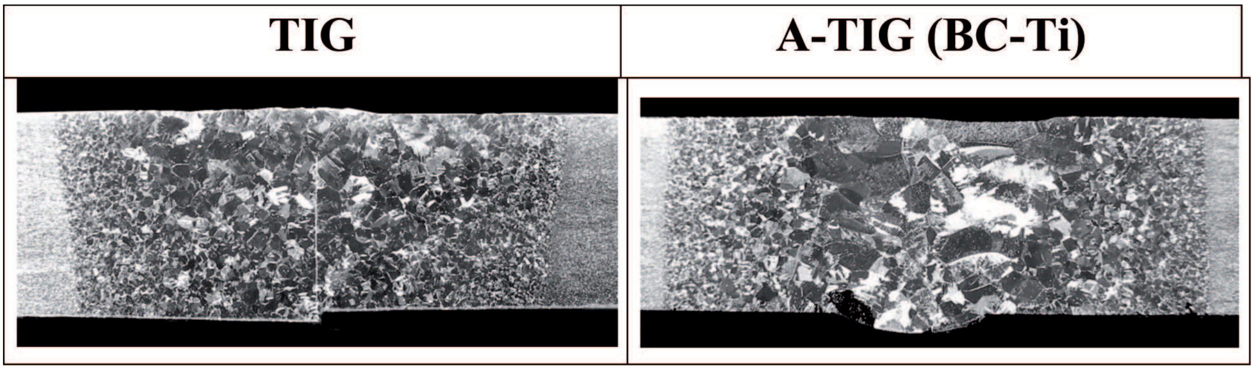

Fig. 5. Macrostructure of butt joints of 5 mm-thick Grade 2 titanium produced by means of TIG and A-TIG methods (Kroll's reagent)

TABLE 2

Mechanical properties of butt welded joint of Grade 2 titanium produced by means of A-TIG method

Sample type	**Material thickness, mm**	**R_m, MPa**	**A_5, %**	**Bend angle 4t, °**		**Impact energy KV_{+20}, J**		
				face	**root**	**weld**	**HAZ**	**2 mm from fusion line**
parent metal	7.4	499.1-498.9 **499.0**	27.3-27.0 **27.15**	–	–	79-81 **80**		
welded joint	5	540.6-527.2 **533.9**	–	–	180 180	18-25 **22**	30-40 **35**	38-42 **40**

TABLE 3

Hardness of individual zones of butt welded joint of 5 mm-thick Grade 2 titanium produced by means of A-TIG method

Sample denotation	**Place of measurement and hardness HV10**														
	Parent metal			**HAZ 1**			**Weld**			**HAZ 2**			**Parent metal**		
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
5Ti A-TIG	155	161	162	156	174	158	182	190	161	159	162	155	164	164	158

The comparative analysis of the macrostructure of the welded joints (Fig. 5) revealed that, in case of the same welding parameters, the A-TIG method makes it possible to obtain a proper joint with complete penetration (penetration depth: 5 mm) after a single run. In turn, in case of the traditional TIG method it is possible to observe the lack of penetration of the root (penetration depth of only 1.2 mm); the aforesaid absence of penetration is indicated by a thin white line in the middle of the joint. The application of BC-Ti activating flux translates to approx. 5-fold increase in the penetration depth.

The values presented in Table 2 indicate that the tensile strength of A-TIG-welded joint is slightly higher than that of the parent metal. The positive results of bend tests conducted on the root side also indicate satisfactory plasticity of the joint material. Bend tests on the face side were not performed due to the presence of a natural notch i.e. a slight concavity of the weld face formed as a result of welding with no filler metal added. The hardness tests revealed that the highest hardness values can be observed in the weld material, yet the hardness of the parent metal and that of the specific zones of the welded joint do not differ significantly (Table 3).

It was only possible to observe significant differences between the impact energy values of the parent metal (79÷81 J), the weld (18÷25 J) and HAZ (38÷42 J) i.e. the areas heated above a temperature of 882°C, at which the process of significant grain growth can be noticed. It should, however, be added that the above structural changes can be also observed during traditional TIG welding. The comparison of impact energy values for both welding methods would be difficult as there is no possibility of producing joints by means of the TIG method using similar parameters. In addition, impact strength tests are not regarded as necessary while qualifying the technology of welding titanium and its alloys according to standard PN-EN ISO 15614-5:2008 [10].

The application of BC-Ti activating flux during A-TIG welding makes it possible to obtain required strength and plastic properties of welded joints.

5. Summary

The application of all activating fluxes (BC-Ti and unary) during A-TIG welding of Grade 2 CP titanium causes increasing of the penetration depth if compared to that obtained during traditional TIG welding. The most significant i.e. 76% increase is related to the application of single component flux in the form of magnesium fluoride (MgF_2). As opposed to A-TIG welding of steel and nickel alloys, in case of A-TIG welding of titanium the application of activating fluxes is, first of all, aimed at increasing the penetration depth, as, due to some specific physical properties of titanium, welding shrinkage does not occur.

The tensile strength and bend tests as well as the measurements of the hardness of A-TIG-welded joint of 5mm-thick Grade 2 titanium produced positive results, which qualifies the above method as having practical application.

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Received: 10 May 2011.