S. L. Schwab, I. K. Petrychenko, S. V. Akhonin

TIG Welding of Titanium Alloy VT22 Performed Using the External Control Magnetic Field

Abstract: The article presents results of tests concerning the effect of transverse magnetic field on the change in the spatial position of arc column during the TIG flux-cored welding of titanium. The tests enabled the development of the multi-run welding of 8 mm thick high-strength titanium alloy VT22 using crosswise magnetic field. It was revealed that the use of transverse magnetic field made it possible to change weld pool solidification conditions as well as to control the shape and dimensions of the weld enabling the obtainment of properly shaped welds characterised by satisfactory quality.

Keywords: TIG welding, titanium alloy VT22

DOI: 10.17729/ebis.2017.6/5

Introduction

Argon-shielded tungsten electrode arc welding (i.e. TIG welding) is the most popular and versatile method used when making welded structures in titanium alloys. Titanium itself and low-alloy titanium alloys are characterised by good weldability and the service life of welded joints (in operating conditions) very similar to that of the base material. In turn, the weldability of high-strength titanium alloys is significantly inferior to that of low-alloy titanium alloys. One of the high-strength titanium alloys is the double-phase alloy ($\alpha + \beta$), i.e. titanium alloy VT22 (Rus. BT22) Ti-5Al-5Mo-5V-1Fe-1Cr. This alloy is widely used in the manufacturing of airplane elements exposed to various forces (e.g. Antonov). The structure of annealed alloy VT22 is composed of nearly the same amounts of phase α and β, being responsible for the high mechanical properties of the alloy.

Because of the fact that alloy VT22 reveals increased sensitivity to the welding thermal cycle, it is of primary importance to create conditions enabling the control of welding arc thermal parameters so that it could be possible to optimise the phase composition and the structure of weld metal. This result can be achieved by controlling the position of the arc column using the external cross-wise magnetic field. The use of the cross-wise magnetic field enables changes in the position of the arc column (in space), the desired disposal of heat input and, consequently, the obtainment of significantly better control over the weld formation process as well as the achievement of higher efficiency, particularly during multi-run welding.

As a conductor in the cross-wise magnetic field, the column of welding arc is subjected to gradual deformation along with increasing magnetic field intensity. During the above-named

S. L. Schwab, I. K. Petrychenko, S. V. Akhonin – E. O. Paton Electric Welding Institute, the National Academy of Sciences of Ukraine, Kiev

process, the cathode spot remains nearly in the same place of the tungsten electrode striking end, whereas the anode spot moves in the direction of the Lorentz force effect. The rate of anode spot movement depends on amplitude, frequency of the cross-wise alternating magnetic field and time.

The peculiar behaviour of arc controlled by the magnetic field increases the technological potential of the former. As a rule, penetration depth is controlled through changes in the proportion of current to a welding rate. An increase in welding current translates into an increase in a welding rate. This, however, may lead to the obtainment of welds having undesirable shapes. The foregoing can be prevented by superimposing the cross-wise magnetic field (directed along the weld axis) on arc, resulting in a decrease in penetration depth and a slight increase in the weld width. A significant change in the weld width during welding in the cross-wise magnetic field can be achieved by controlling the amplitude of the weaving moves of arc. The above-named amplitude is directly proportional to magnetic induction in the arc burning zone. Because of the foregoing, the effect of the cross-wise magnetic field on the formation of welds during the multi-run welding of titanium alloy VT22 requires further research.

The research work aimed to investigate the effect of parameters of the cross-wise control magnetic field on the shape and structure of weld, and, afterwards, on the basis of determined correlations, to develop the technology enabling the flux-cored welding of medium thick titanium alloy VT22 [1].

Devices Generating the Cross-Wise magnetic Field in the Welding Area

The generation of the cross-wise magnetic field in the arc burning area required the development of devices (electromagnet and power source) enabling the control of the arc column position in relation to the weld axis during the welding process (Fig. 1).

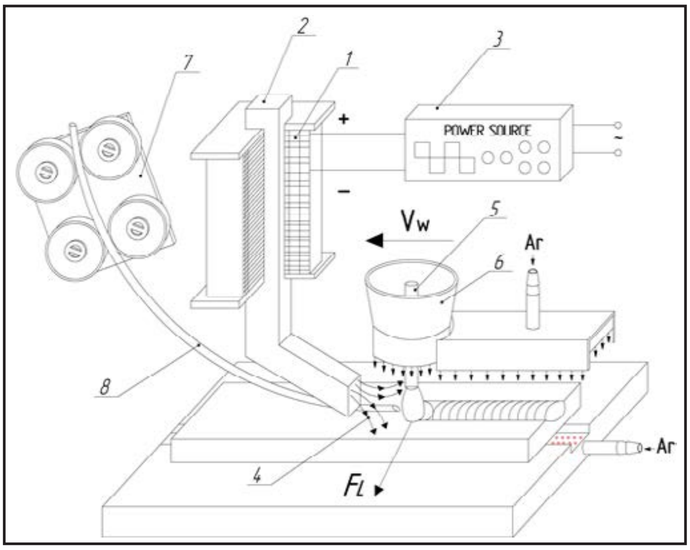

Fig. 1. Schematic diagram of TIG welding in the external control magnetic field: 1 – electromagnetic coil; 2 – electromagnet core; 3 – electromagnet power source; 4 – magnetic induction curves; 5 – tungsten electrode; 6 – shielding nozzle; 7 – filler metal wire feeder; 8 – flux-cored wire; F_L – Lorentz force; V_W – direction of welding

The primary parameters of the control magnetic field include frequency (F), magnetic induction (B [μT]), a pause between impulses (P) and the shape of an impulse.

The electromagnet power source generated impulses of alternating current having a trapezoid waveform with the frequency range of 5 to 50 Hz. The value of magnetic induction in the arc burning zone could be adjusted within the range of 0.4 to 6 μT. A time of pause between impulses changed within the range of 0 to 50% in relation to the general impulse cycle duration (Fig. 2).

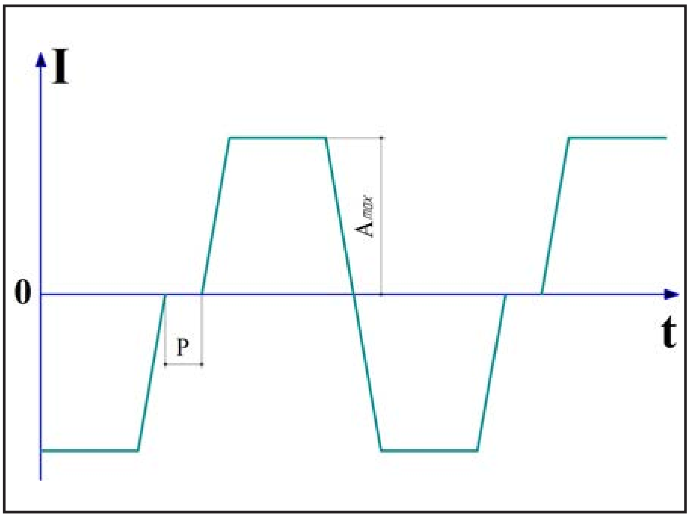

Fig. 2. Shape of the impulse of magnetising current flowing through the electromagnet coil

The face of the electromagnet core was aligned with the flux-cored wire and perpendicular to the tungsten electrode axis. When arc was initiated, the electromagnet power source was started and, as a result, the cross-wise magnetic field was generated. The magnetic field was superimposed on the arc self-field causing its deflection in the direction of the Lorentz force effect. The change in the polarity of the control magnetic field triggered a change in the Lorentz force direction making arc deflect in the opposite direction (Fig. 3).

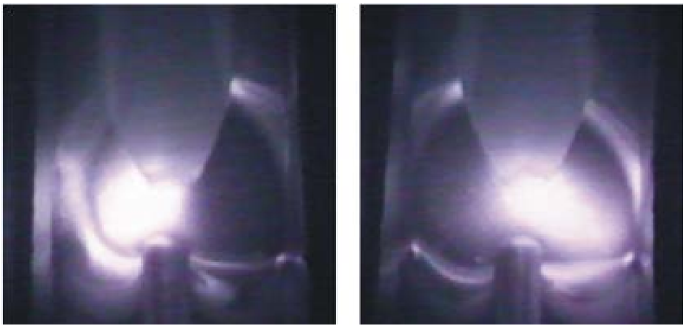

Fig. 3. Arc position limit points when using the magnetic field (video recording)

Testing the Effect of the Cross-Wise Magnetic Field on the Shape of Welds

The identification of correlations between the effect of magnetic field parameters on the formation and solidification of welds involved the making of overlay welds using various magnetic field parameters. The filler metal used in the test was flux-cored wire PPT-22 (Rus. ППТ-22) having a diameter of 3 mm. The cover of the wire was made of titanium alloy VT-1-0 (Rus. ВТ-1-0), whereas its core was a mixture composed of titanium alloy VT22 granules and gas and slag-forming ingredients [1]. Test overlay welds were made on a 6 mm thick plate made of titanium alloy VT1-1 (Rus. ВТ1-1). The experiments were performed using constant surfacing parameters, i.e. a welding current of 200 A ($I_{СВ}$), an arc voltage of 13 V ($U_{Д}$), a surfacing rate of 8 m/h ($V_{СВ}$) and a filler metal wire feeding rate of 26 m/h ($V_{ПОД}$).

The quality of the overlay welds was evaluated on the basis of the macrostructure of related specimens (Fig. 4) subjected to measurements

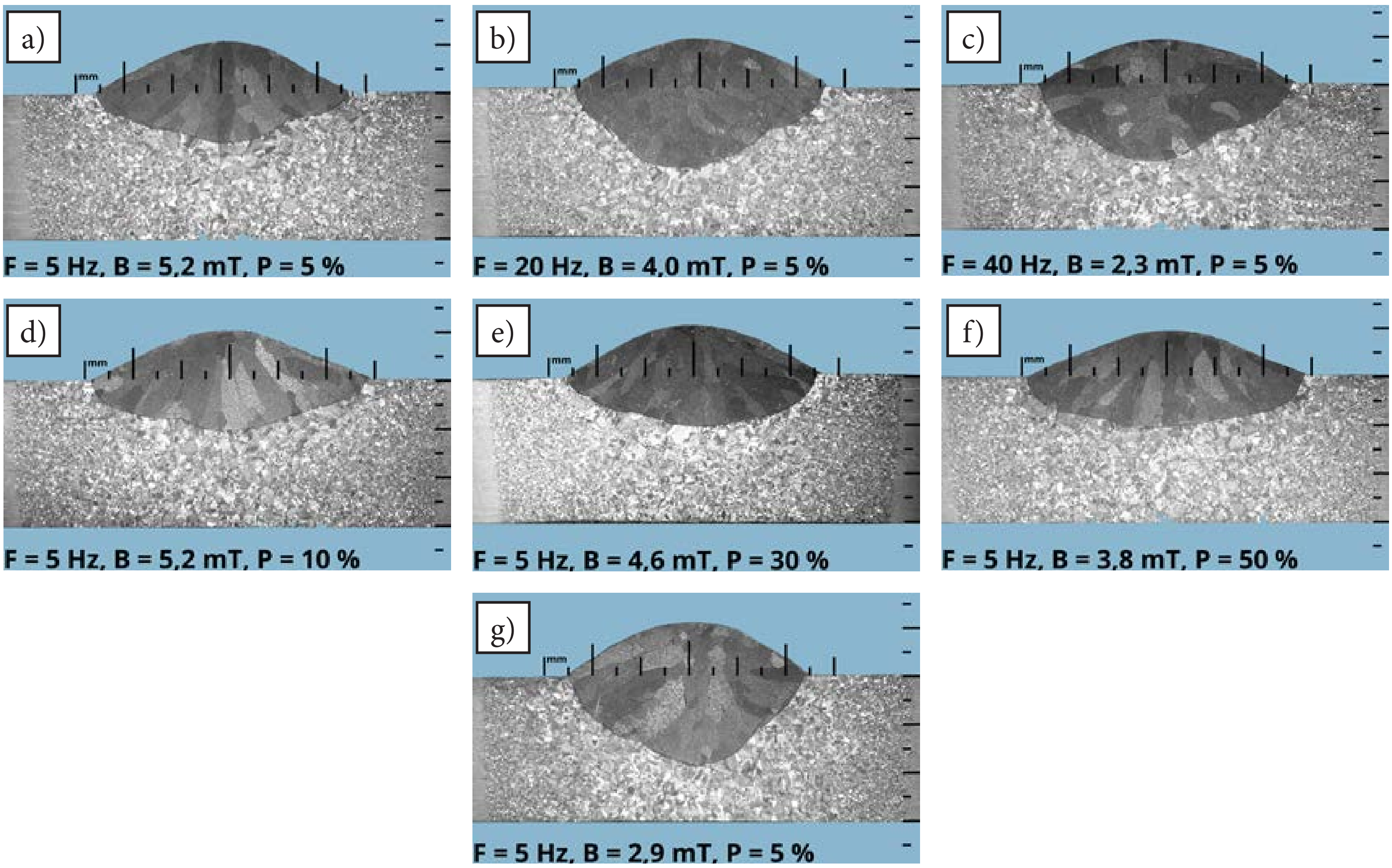

Fig. 4. Shape of overlay welds in relation to various magnetic field parameters presented in the individual photographs of overlay weld macrostructure

of penetration depth (h), weld width (e) and weld height (t) in relation to the magnetic field parameters (Table 1).

Table 1. Correlation between weld dimensions and magnetic field parameters

Magnetic field parameters			**Weld dimensions**		
B, μT	*F*, Hz	*P*, %	*e*, mm	*h*, mm	*t*, mm
5.2	5	5	10.3	2.0	4.2
4.0	20	5	10.4	3.3	5.3
2.3	40	5	10.5	3.1	5
5.2	5	10	11.5	2.1	4.2
4.6	5	30	10.3	2.1	4.2
3.8	5	50	11.5	2.1	4
2.9	5	5	10	3.8	6

The analysis of the overlay weld macrostructure revealed that:

– increase in frequency led to an increase in penetration depth (Fig. 4a, 4b and 4c);
– extension of the pause between impulses nearly did not affect the weld shape and penetration depth (Fig. 4d, 4e and 4f).

The approximation of results (correlation between penetration depth, weld width and weld shape factor (*Kn*) and the value of magnetic induction) involved the use of the least squares method [3], enabling the development of the following equations of linear regression.

– Equation of the linear regression of the correlation between penetration depth and the value of magnetic induction (Fig. 5):

$$h = -0.5 \cdot B + 4.6429 \quad (1)$$

– Equation of the linear regression of the correlation between the weld width and the value of magnetic induction (Fig. 6):

$$e = 0.2764 \cdot B + 9.4657 \quad (2)$$

– Equation of the linear regression of the correlation between the weld shape factor (weld width-weld height ratio) and the value of magnetic induction (Fig. 7):

$$Kn = 0.2324 \cdot B + 1.3919 \quad (3).$$

The analysis of the correlations identified in the tests (Fig. 5-7) justified the conclusion that an increase in magnetic induction was accompanied by a decrease in penetration depth and an increase in the weld width as well as in the weld shape factor.

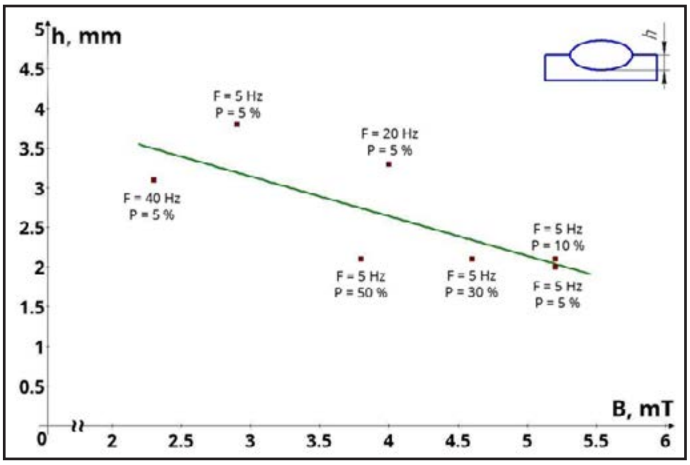

Fig. 5. Correlation between the penetration depth and the value of magnetic induction

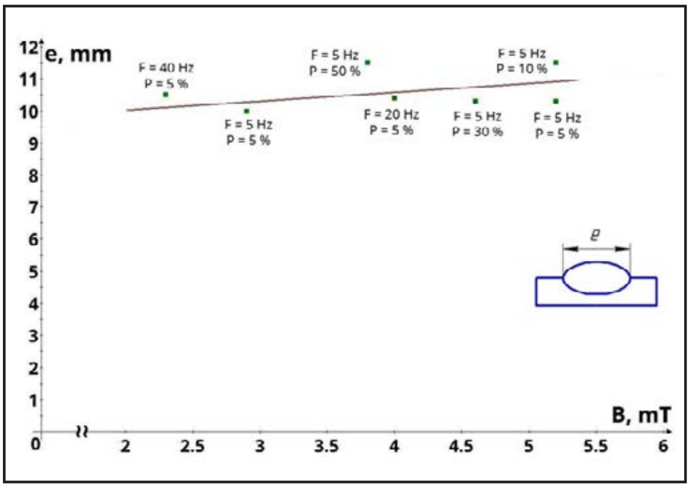

Fig. 6. Correlation between the weld width and the value of magnetic induction

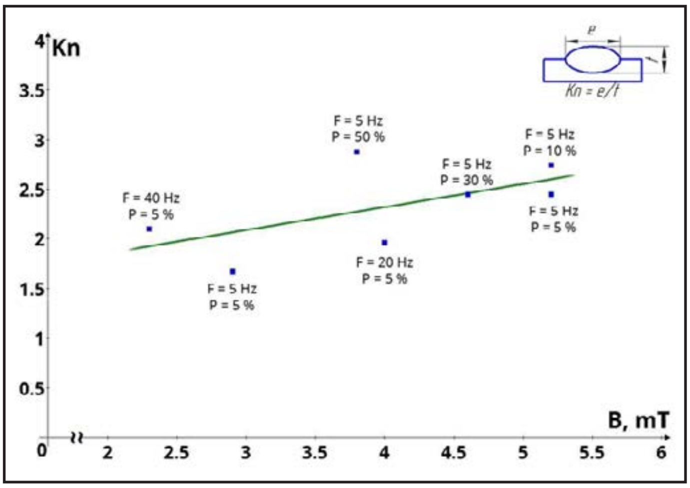

Fig. 7. Correlation between the weld shape factor and the value of magnetic induction

Development of TIG Method-Based Welding of Titanium Alloy VT22 Using Cross-Wise Magnetic Field*

The development of the technology was supervised by V.P. Priłucki, PhD (DSc) Eng.

The maximum penetration depth of 3.5 mm was obtained using the minimum values of magnetic field parameters (Fig. 4g). In the above-presented case, the nature and the depth of the penetration corresponded to the process of surfacing performed without the use of the magnetic field. As a result, it is recommended that (during multi-run welding) the root run be made without using the magnetic field.

During welding in the groove, after the making of the root run, it is recommended that subsequent runs be made using the cross-wise magnetic field. Because of the fact that an increase in frequency and the extension of a pause do not significantly affect the shape of welds, the use of the minimum values of the above-named parameters, i.e. F = 5 Hz and P = 5% is recommended. The widest run and the shallowest penetration depth are obtained when magnetic induction amounts to 5.2 μT. Therefore, the use of the above-named magnetic field parameters ensures the joining of the groove edge with the previous run and the obtainment of required excess weld metal.

The obtained test results enabled the development of a multi-run welding process where the root run is made without the use of the magnetic field and the subsequent runs are made using the magnetic field, enabling the melting of the edges of elements being joined when making the face run [1].

Experiments concerning the welding of alloy VT22 were performed using 8 mm thick plates. The aforesaid thickness requires the performance of V-shaped scarfing and an angle of 90° as well an edge of 1 mm [2]. The filler metal used in the test was flux-cored wire PPT-22. The welding process involved the making of three runs. The magnetic field parameters for runs no. 2 and 3 included a frequency of 5 Hz, a magnetic induction of 5.2 μT and a pause of 5%. The experimentally determined welding parameters (Table 2) were restricted within the range of parameters related to the welding of 8 mm thick alloy VT22 [2]. The above-named parameters enabled the obtainment of welded joints characterised by the full penetration of the edge on the face side, sufficient excess weld metal (1.5 mm) and the satisfactory shape of the weld on the root side (Fig. 8).

Table 2. Welding parameters in relation to the test joint made of alloy VT22

Run no.	Welding parameters			
	$I_{СВ}$, A	$U_{Д}$, V	$V_{СВ}$, m/h	$V_{ПОД}$, m/h
1	200	13.0	9	30
2, 3	220	13.5	7	30

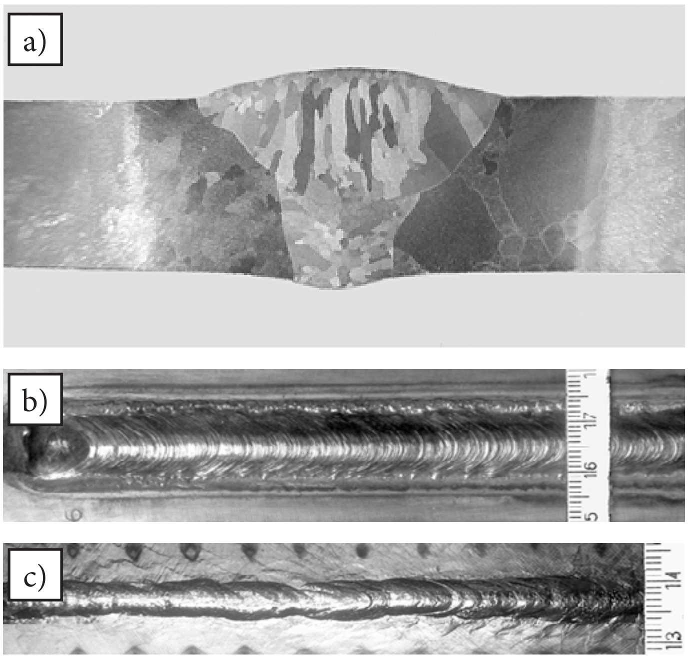

Fig. 8. Test (TIG welded) joint made of 8 mm thick alloy VT22 using flux-cored wire PPT-22: a) – macrostructure of the welded joint; b) – weld face; c) – weld root

The service life and economic efficiency of welded structures depend significantly on the quality of welded joints. Imperfections in welded joints frequently trigger unacceptable changes in operational properties of products. The most common welding imperfection accompanying the inert gas-shielded welding of titanium is porosity. Gas pores in welds, particularly

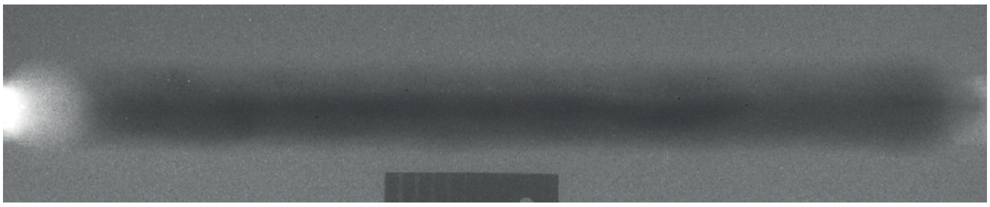
Fig. 9. X-ray photograph of the welded joint made using flux-cored wire PPT-22

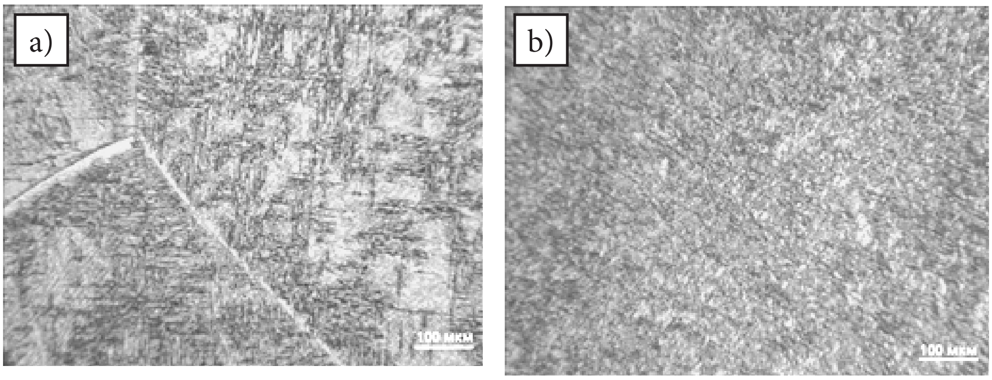

Fig. 10. Welded joint microstructure: a) not exposed to the magnetic field; b) exposed to the magnetic field

during the welding of high-strength titanium alloys are the primary reason for the reduced service life of welded structures exposed to cyclic loads. It was ascertained that welds made of dual-phase ($\alpha + \beta$) titanium alloys are more susceptible to develop porosity in comparison with single-phase alloys. Repeated studies revealed that one of the primary technological procedures preventing the formation of porosity in the weld metal of titanium and its alloys during inert gas-shielded welding is the use of flux-cored wires containing appropriate gas and slag-forming ingredients as the use of flux intensifies the degassing of the weld pool [2]. The X-ray examinations of the welded joint confirmed that the use of the flux-cored wire prevents the formation of porosity in the weld (Fig. 9).

Welded Joint Structure and Properties

The comparison of the microstructure of the metal of the welds exposed to the magnetic field and those obtained without this effect revealed that the use of the alternating magnetic field not only makes it possible to control the dimensions of the weld but also affects the conditions of the weld pool solidification process, thus contributing to the formation of a more uniform and homogenous microstructure. Welding performed without the use of the magnetic field resulted in the heterogeneous structure of grains. The structure contained areas revealing intense transformations and the high density of lamellar martensitic phases as well as bright areas with the lower density of martensitic phases indicating the non-uniform transformation of solid solution β (Fig. 10a). The weld pool exposed to the magnetic field effect is characterised by the higher uniformity of the solid solution transformation as well as by the formation of a more homogenous microstructure (Fig. 10b).

The effect of the crosswise magnetic field on the motion of liquid metal in the weld pool enables changes in the primary structure of solidifying metal. Arc moving over the weld pool triggers the motion (induced by electromagnetic field) of the liquid metal located directly under arc. The intense stirring of liquid metal changes solidification conditions and enables the obtainment of the fine-grained weld microstructure.

After welding, joints are usually subjected to annealing (heat treatment). An effective method enabling the improvement of the plastic properties of alloy VT22 is high-temperature annealing in the dual-phase structure area performed within the temperature range of 750 to 800°C followed by cooling (along with the furnace). The purpose of the annealing process involves the removal of welding process-induced stresses and the obtainment of a uniformly arranged and homogenous structure characterised by the required phase α – phase β ratio. The tests involved the use of a relatively easy method (in terms of technological conditions) of the heat treatment of welded joints made using the flux-cored wire, i.e. annealing at $T = 750°C$ for 1 hour followed by cooling (along with the furnace).

The macro and microscopic tests of the weld metal subjected to heat treatment revealed that the process of annealing led to the formation of the uniform and homogenous metal structure across the entire cross-section of the weld (Fig. 11 and 12). The accompanying transformation of metastable phases had a favourable effect on the weld metal strength, which turned out to be higher than that of the base material (Table 3).

After welding, the mechanical properties of the weld metal and those of the base material were similar. In turn, the plastic properties of the joint were by 1.5 times lower than those of the base material. After the heat treatment process, the toughness of the weld metal constituted 70÷75% of the base material toughness.

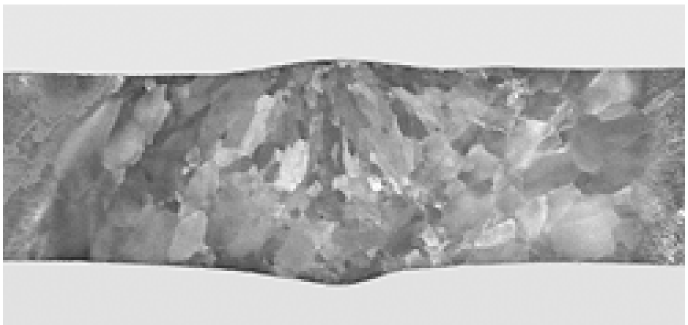

Fig. 11. Macrostructure of welded joint made of 8 mm thick alloy VT22, subjected to heat treatment

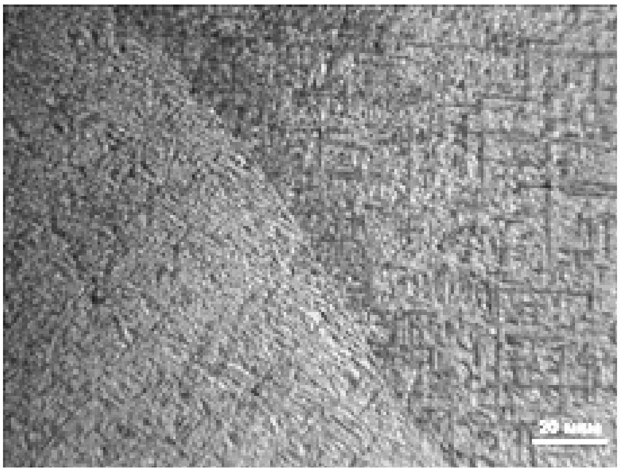

Fig. 12. Microstructure the welded joint made of alloy VT22, subjected to annealing

Table 3. Mechanical properties* of the welded joint and base material after annealing

Status	Test area	σ_{YS}, MPa	σ_{UTS}, MPa	*El*, %	*RA*, %	KCV, J/cm^2
After welding	Base material	974.1	1057.5	13.3	33.3	19.6
	Welded joint	987.7	1065.1	9.0	23.9	5.9
After heat treatment	Welded joint	-	1121.5**	-	-	14.8

* mean values of tests involving three specimens
** fracture in the weld

Conclusions

1. The cross-wise alternating magnetic field makes it possible to control heat distribution in the welding area, and, consequently, to control the shape and dimensions of welds.

2. The tests revealed that the use of the cross-wise magnetic field enables the formation of the more uniform and favourable weld metal structure and favours the uniform transformation of phase β during cooling as well as makes it possible to obtain satisfactory properties of the weld metal after welding and annealing.

3. The tests enabled the identification of the technological parameters of the cross-wise magnetic field and, based on the results obtained in the tests, made it possible to develop a TIG method-based welding technology with magnetically controlled arc, extending the application of the method during multi-run welding.

References

[1] Прилуцкий В. П., Шваб С. Л., Петриченко И. К. и др.: *Аргонодуговая сварка титанового сплава ВТ22 с использованием присадочной порошковой проволокой*. Автоматическая сварка, 2016, no. 9, pp. 10-14.

[2] Гуревич С. М., Замков В. Н., Блащук В. Е. и др.: *Металлургия и технология сварки титана и его сплавов. 2-е изд., доп. и перераб*., Наук. думка, 1986.

[3] Радченко С. Г.: *Методология регрессионного анализа: Монография*. Корнийчук, 2011.
[4] Ильин А. А., Колачев Б. А., Полькин И. С.: *Титановые сплавы*. Состав, структура, свойства. ВИЛС-МАТИ.
[5] Paton B. E., Zamkov V. N., Prilutsky V. P.: *Narrow-groove welding proves its worth on thick titanium*. Welding Journal, 1996, no. 5, pp. 37-41.
[6] Размышляев А. Д., Миронова М. В.: *Магнитное управление формирование валиков и швов при дуговой наплавке и сварке*. Изд-во ПГТУ, 2009.
[7] Лясоцкая В. С.: *Термическая обработка сварных соединений титановых сплавов*. Экомет, 2003.
[8] Хорев А. И.: *Легирование и термическая обработка (α+β)- титановых сплавов высокой и сверхвысокой прочности*. Технология машиностроения, 2009, no. 1, pp. 5-13.
[9] Lutjering G., Williams J. C.: Titanium [M]. Springer Verlag, Germany, 2003. http://dx.doi.org/10.1007/978-3-540-71398-2
[10] Иноземцев А. А., Башкатов И. Г., Коряковцев А. С.: *Современные титановые сплавы и проблемы их развития*. ВИАМ, 2010.