THE INFLUENCE OF ELECTRIC ARC ACTIVATION ON THE SPEED OF HEATING AND THE STRUCTURE OF METAL IN WELDS

by

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Original scientific paper
DOI: 10.2298/TSCI140530125S

This paper presents the results of a research related to the impact of electric arc activation onto drive welding energy and metal weld heating speed. It is confirmed that activated tungsten inert gas welding and activated metal inert gas welding methods, depending on metal thickness, single pass weldability and chemical composition of activating flux, enable the reduction of welding energy by 2-6 times when compared to conventional welding methods. Additionally, these procedures create conditions to increase metal weld heating speed up to 1,500-5,500 °Cs^{-1}. Steel which can be rapidly heated, allows for a hardened structure to form (with carbon content up to 0.4%), together with a released martensitic structure or a mixture of bainitic-martensitic structures. Results of the research of effectiveness of activated tungsten inert gas welding and activated metal inert gas welding showed that increase in the penetration capability of electric arc, which increases welding productivity, is the visible side of activated tungsten inert gas welding and activated metal inert gas welding capabilities.

Key words: *arc welding, active flux, penetration, heating speed, driving energy*

Introduction

In the 1960s of the last century, in a variety of industries and in a number of industrialised countries began using high-purity steel, characterised by a very low content of harmful impurities such as sulphur, phosphorus, gases, *etc.* The content of these impurities was reduced when compared to conventional constructional steel [1].

Increased steel chemical purity has enabled the improvement of its properties: increase in plasticity and cracking resistance. But with the rapid weakening of the penetration capability of electric arc, the conditions for the formation and properties of welding joints worsened. Solving these problems at the expenses of increasing the welding current has only worsened the already complex situation. Penetration depth has negligibly increased, but the width of the seam was growing up intensively, and intensive grain growth was observed in the heat affected zone (HAZ).

The reason for the deterioration of the formation of weld metal and its quality in steel, as shown by the research conducted at E. O. Paton Electric Welding Institute [1], is a sharp de-

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crease of sulphur and oxygen. This was the reason to start our scientific research, which has been directed towards the increase in the penetration capability of electric arc within the protection of inert gases. The result of this research are the confirmed recipes of special activating fluxes. Their use in arc welding with insoluble electrode within the protection of argon (activated tungsten inert gas – ATIG) allowed for an increase in electric arc energy concentration. At the same value of the arc thermal power, as in the conventional tungsten inert gas (TIG) welding, penetration has increased 2-3 times. Maximum efficiency when it comes to the application of activating fluxes is achieved while welding high-purity steel, and was gradually decreased as the degree of steel purity also decreased. But even during ATIG welding of general purpose construction steel with maximum content of sulphur and oxygen, the penetration depth is approximately 1.5 times higher when compared to conventional TIG welding.

This technological advancement in the former Soviet Union was applied in aeronautics, missile industry, and nuclear energetics. During the 1990s of the last century, ATIG procedure was presented and approved by the British Institute of Welding, which confirmed the feasibility of its application.

Currently, researches on the application of the activating fluxes are conducted in the UK, USA, Japan, China, Russia, Poland, Montenegro, and other countries. In Ukraine, in co--operation with the Montenegrin researchers, while at the same time developing activators to master ATIG welding technology, researches were conducted to improve metal inert gas (MIG) welding procedure. The result of these researches is the development of activated metal inert gas (AMIG) process, *i. e.* arc welding activation application with welding wire. Activating soluble fluxes are used welding with welding wire, which allows increased penetration of electric arc 2-4 times when compared to conventional MIG process.

However, as the testing results of ATIG and AMIG welding processes effectiveness have demonstrated, an increase in the arc penetration capability, which causes an increase in welding productivity, is only the external, visible side of their capabilities. Technological capabilities of these processes allow for a controlled impact on the conditions of formation of the welding joint, its structure and its properties.

With the conventional method, which implies the improvement of welding joints quality, we exert influence on it in the cooling process [2]. Heating process is not used for these improvements, as the researchers conducted under the leadership of Gridnev [3] on the effect of heating at high speeds during thermal treatment of hardened steel, answered what is the impact of this period on their structure and properties. Effect of warm-up period during the welding processes was analysed and discussed by a group of authors [4]. Based on the research, they concluded that the increase in heating rate contributes to the increase of A_{c3} temperature point. When heating up to 3000 °C, when it comes to steel with carbon content up to 0.4%, the temperature of A_{c3} point may have the value of over 1000 °C, with a tendency to increase as heating speed increases [5-7]. In this way, it reduces the temperature interval of austenite grain growth and homogenisation, which contributes to the increase in the number of new phase creation centres and shift its breakup while cooling into the elevated temperature area. At the same time, the higher the heating rate, the lower the level of homogeneity of austenite and the higher the temperature area of its breakup while cooling.

The ATIG welding experiment and analysis results

New methods of the implementation of high-speed heating during welding are mastered, which allowed the control of the formation of structure and properties of joints by arc welding of hardened steel and its welding without preheating. Combining rapid heating with adequate thermal heating (thermo cycle) allows welding without overheating of steel with carbon content up to 0.8% [8].

Metal heating speed while welding determines driving energy [9], which represents the ratio of arc thermal power (q) and welding speed (V_w), *i. e.* q/V_w. Arc thermal power (q) is determined according to the equation:

$$q = I\,U\,\eta \tag{1}$$

As visible on dependence curves showing dependency of heating rate on driving energy (fig. 1), any change in arc thermal power and welding speed, in order to reduce driving energy value, is accompanied by an increase in the heating rate of the welding joint metal. In addition, the intensity of the influence of welding speed is much higher than arc thermal power. Hence, arc activation, which increases the penetration by several times when compared to the conventional welding method, enables the reduction of drive energy while welding the metal of the same thickness. Also, the activation increases the speed of heating of welding joint metal.

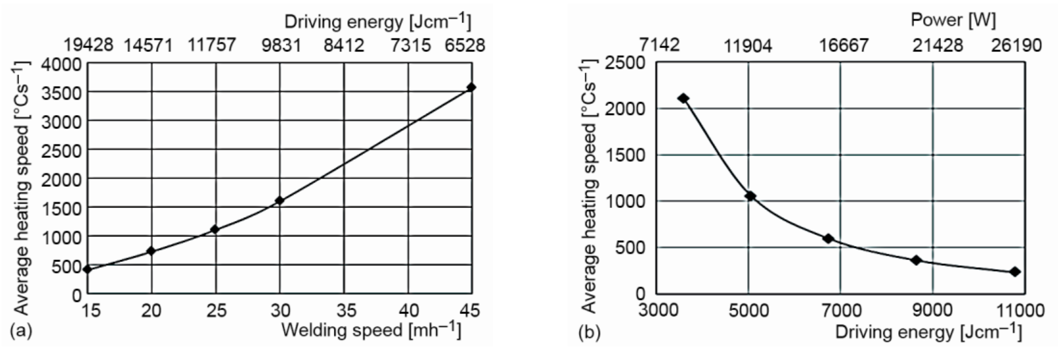

Figure 1. Effect of driving energy of welding on the heating speed of metal weld (≠ 10 mm); (a) the influence of welding speed, (b) the influence of arc heat power

Therefore, the aim and the objective of this paper is to study the influence of the activation properties of electric arc welding on drive energy, speed of heating of welding joint metal and its structure.

Table 1 shows the results of the testing related to the character and degree of impact of activating fluxes on driving energy in argon shielded arc welding in relation to metal of equal thickness of 3.5 mm and 6 mm. Welding thermal cycle was determined by experimental methods and calculated by using the experimental data according to the method devised by Rikalin and Pugin [10].

Table 1. Influence of the activation of arc on drive energy in arc welding with the soluble electrode shielded in argon

Thickness of the material, [mm]	Welding process	Driving energy, [Jcm^{-1}]
3.5	Without activating flux	5890
	With one-component activator	3600
	With multi-component activating flux	2162
6	Without activating flux	11520
	With one-component activator	6864
	With multi-component activating flux	6057

From tab. 1 it is evident that the full penetration of metal, the thickness of which is 3.5 mm, while using the conventional arc welding in argon protection, requires driving energy of 5890 J/cm. By applying a single component activator, it is possible to reduce driving energy down to 3600 J/cm, which is approximately 1.64 times less when compared to the conventional method. Application of a multicomponent activator provides an even greater effect. By applying a multicomponent activator, for metal (3.5 mm in thickness), it is possible to reduce driving energy down to 2162 J/cm, which is approximately 2.72 times less when compared to the conventional method.

However, it should be noted that the effect of the activation of electric arc on driving energy while welding with insoluble electrode gradually decreases with the increase in thickness of welded metal (tab. 1). An example is welding of metal with its thickness of 6 mm. When comparing, we can see that for the single pass welding with the full penetration of the same thickness of metal with TIG process, the necessary driving energy is 11520 J/cm. By applying the single component activating flux, it is possible to reduce driving energy down to 6864 J/cm (app. 1.68 times less), and by applying the multicomponent activating flux down to 6057 J/cm, *i. e.* approximately 1.90 times less than the conventional method.

As metal thickness increases, which is weldable in one pass, the effectiveness of the influence of the activation of electric arc on driving energy of welding, *i. e.* thermal properties of welded materials is further decreased.

The thermal condition of welding joints is most notably illustrated by welding thermal cycle. Figure 2 shows the thermal cycle values in the HAZ of welding joints during TIG welding in argon protection, obtained in one pass complete penetration of steel (thickness of 3.5 mm), with driving energy which corresponds to data from tab. 1. By using the given welding thermal cycles, we calculated average heating rate in the HAZ of welding joints. The calculation results are shown in tab. 2.

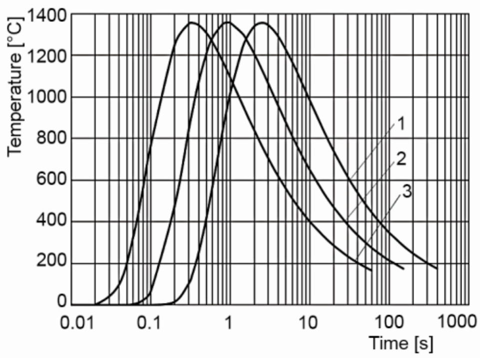

Figure 2. Thermic cycles of the HAZ in one pass argon shielded electric arc welding of metal with thickness of 3.5 mm, obtained with driving energy values of: (1) 5890 J/cm, (2) 3600 J/cm, and (3) 2162 J/cm

Table 2. Average speed of metal heating in the HAZ in argon shielded electric arc welding of metal with thickness of 3.5 mm

Material thikness, [mm]	Welding process	Driving energy, [Jcm^{-1}]	No. of thermal cycles according to fig. 2	Average heating speed, [°Cs^{-1}]
3.5	Without activating flux	5890	1	546
	With one--component activator	3600	2	1500
	With multi--component activating flux	2162	3	4042

Data comparison (tabs. 1 and 2, and fig. 2) confirms that arc activation while welding metal (thickness of 3.5 mm) allows welding driving energy decrease from 5890--2162 J/cm, *i. e.* by more than 2.7 times. At the same time, heating rate of the welded metal increases from 546-4042 °C/s, *i. e.* by 7.4 times. The reason for such influence of the multicomponent activating flux on these processes is the oxidation-reduction reactions at the surface of the liquid metal. Thanks to these reactions, easily soluble, easily ionised impurities are combined into refractory clay, thus preventing its evaporation in arc atmosphere. These impurities usually widen the arc column and reduce the concentration of the energy in it, and consequently, reduce arc penetration ability.

Figure 3 shows the heat cycles of the HAZ of steel welds (6 mm in thickness), obtained from the single-pass welding of full penetration where the values of drive energy are the same as provided in tab. 1. Average heating speed values of these welding joints are shown in tab. 3. Data confirm that, even in this case, the rule is preserved and is very similar to the welding of steel (thickness 3.5 mm), although the heating speeds are lower.

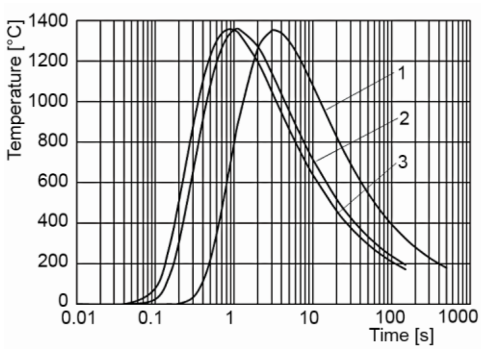

Figure 3. Thermic cycles of the HAZ in one pass welding metal joints, the thickness of which is 6 mm, obtained with driving energy of: (1) 11500 J/cm, (2) 6864 J/cm, and (3) 6057 J/cm

Table 3. Average metal heating speed in the HAZ in argon shielded electric arc welding of metal – thickness 6 mm

Material thikness, [mm]	Welding process	Driving energy, [Jcm^{-1}]	No. of thermal cycles (fig. 3)	Average heating speed, [$°Cs^{-1}$]
6	Without activating flux	11520	1	416
	With one--component activator	6864	2	1184
	With multi-component activating flux	6057	3	1500

This is connected with the necessity to increase driving energy for the penetration of metal – 6 mm in thickness. Thus, for example for the penetration of metal with its thickness of 3.5 mm, without activating flux, it is necessary to achieve drive energy of 5890 J/cm (tabs. 1 and 2). For the penetration of metal, the thickness of which is 6 mm, it is necessary to increase drive energy by approximately 2 times, *i. e.* up to 11520 J/cm (see tab. 1). In the one-component activator, driving energies necessary for the single pass welding of metal sheets of 3.5 mm and 6 mm are 3600 J/cm and 6864 J/cm, according to tab. 1. But in this case the difference between them is 1.91 times. For the single pass welding of metal sheets of 3.5 mm and 6 mm, the multi-component activating flux allows to minimize driving energy down to 2162 J/cm and 6057 J/cm, according to tab. 1. The difference between them is approximately 2.8 times.

So, in the single-pass welding of metal (6 mm in thickness) without arc activation, as confirmed by thermal cycle (fig. 3, curve 1) and the data from tab. 3, heating speed is 416 °C/s. One component activator (fig. 3, curve 2) allows for the increase in heating speed to 1184 °C/s (tab. 3), and with multi-component activating flux up to 1500 °C/s.

Therefore, while welding the metal of 6mm in thickness, the use of activating flux allows the reduction of driving energy by approximately 2 times (tab. 3) and increase of welding speed of metal by approximately 3.6 times. Comparing this data with the same data when welding the metal of 3.5 mm in thickness, leads to the conclusion that with the increase of the thickness of the welded metal by 1.7 times, the effectiveness of the influence of ATIG on driving energy is reduced by 2 times and on metal heating speed by 2.7 times.

However, the welding speed is still quite high, since the positive effect of the welding speed on the kinetics of the welding structural transformations, occurs at heating speed which is greater than 500 °C/s [8, 9]. As the experimental studies show, this heating rate for

ATIG process is achieved when driving welding energy is 8000-9000 J/cm [9]. Depending on the chemical composition of the activating flux, with such driving energies, single pass welding of steel is achieved in about 7-8 mm. While welding some other thicker steel, heating speed is reduced to the values which do not have positive impact on the structure and properties of welding joints in the welded metal joints. It should be noted, with manual arc welding, effects of penetration while using ATIG, also fit into the previously described results, but the values shall be lower by 15-25% than in mechanised welding.

The AMIG welding experiment and analysis results

The positive influence of arc activation on heating speed while welding steel which is thicker than 8 mm, allows welding with welding wire in the protection of inert gases – AMIG process.

Table 4 and fig. 4 show the results of the research, which makes it possible to carry out AMIG impact assessment process on welding driving energy, thermal condition of the weld, and steel heating speed. They show that in the single-pass welding (10 mm in thickness) with welding wire in the shielded gas (MIG) the necessary driving energy is 24,964 J/cm (tab. 4), which corresponds to the thermal cycle 1 (fig. 4). Average heating rate of metal in the corresponding case is 263 °C/s.

Increased arc penetration capability by 1.8 times in AMIG welding enables the decrease in driving energy by approximately 2.7 times – down to 9189 J/cm and increases welding speed up to 1840 °C/s (approximately 7 times). These conditions correspond to the thermal cycle 2 (fig. 4).

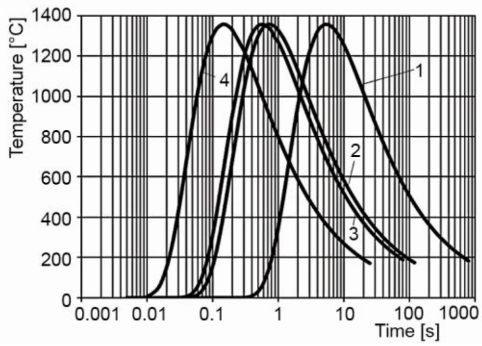

Figure 4. Thermal cycles of the HAZ in the one pass argon shielded electric arc welding of metal, the thickness of which is 10 mm, obtained with driving energy of [11]: (1) 24964 J/cm, (2) 9189 J/cm, (3) 8103 J/cm, and (4) 4400 J/cm

Table 4. Influence of arc activation on driving energy in arc welding with the welding wire shielded in argon

Welding process	Penetration of electric arc, [mm]	Thickness of material, [mm]	Driving energy, [Jcm^{-1}]	Average heating speed, [$^oCs^{-1}$]
Without activating flux	1	10	24964	263
With activating flux	1.8	10	9189	1840
With activating flux	2.0-2.5	10	8103	2760
With activating flux	3-4	10	4400	5500

Further increase in arc penetration capability by 2-2.5 times, allows the reduction of driving energy down to 8103 J/cm, approximately 3 times less when compared to MIG process, and allows the increase in heating speed by approximately 10.5 times – up to 2760 °C/s (tab. 4). In fig. 4, these conditions correspond to the thermal cycle 3.

The increase in arc penetration capability by 4 times when compared with conventional MIG welding, allows the reduction of driving energy required for steel welding (10 mm in thickness), down to 4400 J/cm, which is approximately 5.7 times less than with MIG welding (tab. 4). Heating speed increases at the same by approximately 21 times (fig. 4, curve 4), *i. e.* up to 5500 °C/s (tab. 4).

This data confirms that the application of activating flux while using welding wire for several times, reduces driving energy without the negative impact on the productivity of the welding process. At the same time, the speed of heating of the metal in welding joint is increased. Also, it should be noted that the effectiveness of the impact of activating flux on these processes depends on its chemical composition.

The results of metallurgical tests confirmed that the application of activating flux for welding of hardened steel with carbon content of up to 0.3-0.4% allows the formation of martensitic structure in metal welding joints with varying degrees of self-release, or the formation of mixed bainitic-martensitic structure (fig. 5), with the different percentages release in different phases. Such structures, as it is known, are characterised by rather high strength parameters, plasticity, and cracking resistance. Moreover, while increasing the heating speed of metal of welding joint, the degree of self-release of martensitic structures increases, and the percentage content of bainitic structures increases and can exceed 50%. In rare cases, bainitic component overcomes the percentage content of martensitic. This proves that, with the increase of heating speed of metal of welding joint, the transformation of cooled austenite gradually moves to the highest high-temperature bainitic (transitional) areas. Therefore, due to arc activation, we have an increase in heating speed and the level of homogenisation of austenite gradually decreases, which fully corresponds to the results of the testing [3, 5-7].

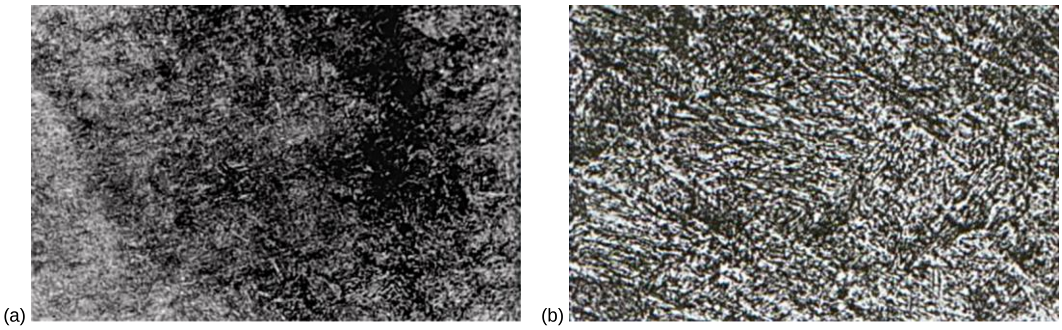

Figure 5. Microstructure of the metal of welding joints, obtained from arc activation: (a) released martensite (× 240), (b) bainite-martensite mixture (× 400)

In this manner, electric arc activation, allows the implementation of control and management of the process of forming the metal structure of the welding joints in the welding process.

Conclusions

Activation of the electric arc welding with both insoluble and soluble electrode shielded in gases, depends on the thickness of the metal, single pass weldability and chemical composition of the activating flux, which allows the reduction of driving energy by 2-6 times when compared to the conventional welding method.

Reduction of the welding driving energy on the account of arc activation by more than 2-6 times, is followed by an increase in heating speed of the metal of welding joints, which in ATIG and AMIG processes can reach values of up to 1500-5500 °C/s.

Effectiveness of rapid warming in ATIG process, is preserved while welding the metal, the thickness of which is 7-8 mm, and while welding thicker metals, it is rational to use AMIG process.

High values of heating speed allows the creation of released martensitic structure or a mixture of bainitic-martensitic structures in metal welds of hardened steel with carbon content of up to 0.4%. With increasing the heating speed of metal welds, the degree of self-release of martensite increases and the percentage of bainite grows. This allows for the welding of medium-carbon steel without preheating.

Nomenclature

A_{c3} – temperature at which, during heating, the transformation of ferrite into austenite is ended, [°C]
I – welding current, [A]
q – arc thermal power, [W]
q/V_w – driving energy, [Jcm^{-1}]
U – arc voltage, [V]
V_w – welding speed, [mh^{-1}]

Greek symbols

η – effective coefficient of usefulness of electric arc – the part of electric arc energy which is spent on metal melting

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Paper submitted: May 30, 2014
Paper revised: October 4, 2014
Paper accepted: October 23, 2014