INFLUENCE OF THERMOPHYSICAL PROPERTIES OF MATERIALS ON FORMATION CONDITIONS AND QUALITY OF WELDED JOINTS

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Abstract:

Modern methods for estimating the conditions for the formation of high quality welded steel compounds are based on the data of their chemical composition. Research shows that the conditions of formation and the quality of welded joints, as well as the welding regime, are directly dependent on the thermophysical properties of the materials, as well as the character of their change during this process. Due to the formation of the austenite layer as a heat barrier, the development of processes leading to the occurrence of hot or cold cracks is facilitated. The dimensions of the heat barrier and the degree of its negative impact on the quality of the welded joint are increased with increasing heat input during welding. Therefore, it is necessary to lower the energy capacity of the welding process and increase the concentration of material heating. An effective method of reducing the dimensions of the thermal barrier and the time interval of its existence is the activation of physical and chemical processes in the electrical arc during welding in a protective atmosphere. The results of our tests show that the effectiveness of activating fluxes depends not only on their chemical composition but also on the thermostability of its components and thermophysical properties of welded materials.

1 INTRODUCTION

One of the priority directions of arc welding development is to reduce energy consumption during this technological process while at the same time increasing the productivity and quality of welded joints. The difficulties that occurred during the welding of materials, primarily iron-based materials, conditioned intensive work on the development of hybrid welding processes. The welding process which combines laser and electric arc provide the high-quality welded joint with the most commonly used structural carbon steel, as well as high-strength steel. Welded joints are characterized by a favorable structure, high toughness and resistance to cracks, while simultaneously increasing productivity and decreasing energy consumption.

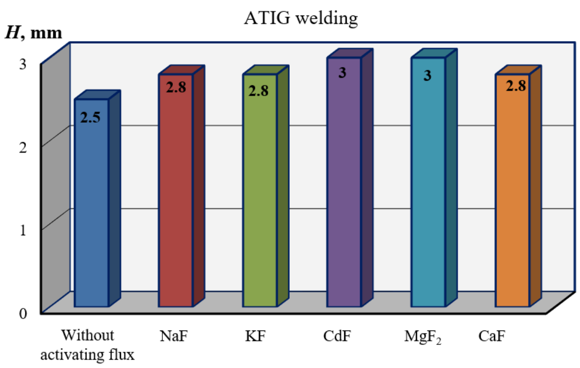
The formed thin austenitic layer in the heat affect zone (HAZ), defined as the thermal barrier, is characterized by minimal thermal conductivity and high thermal capacity. This layer has the ability to accumulate and retain a significant amount of heat, thus providing the preconditions for the emergence of cracks, as well as the formation of a coarse grain structure of the weld metal. The dimensions of the thermal barrier and the degree of its negative impact on the quality of the welded joint are increased with increasing heat input during welding. Therefore, it is necessary to lower the energy capacity of the welding process and increase the concentration of material heating. The solution of this complex problem is the activation of physical-chemical processes in the electrical arc during welding in the protective atmosphere of inert, active or gas mixtures. These methods of fusion welding are known in the literature as ATIG (TIG welding using activating flux) and AMIG (MIG welding using activating flux) welding processes. The results of the study show that by using specially prepared activating fluxes in arc welding in a protective atmosphere, the penetration of the electric arc is increased 2-4 times, while simultaneously reducing the energy consumption up to 6 times [1,2].

Numerous experiments in the field of the manufacture and application of activating fluxes in TIG welding [3-8] confirm that there is a wide application of fluoride and oxide. Also, there are studies on the use of chloride-based activating fluxes [8], but their use is not recommended due to the high level of toxicity of steam and gases generated during the welding process.

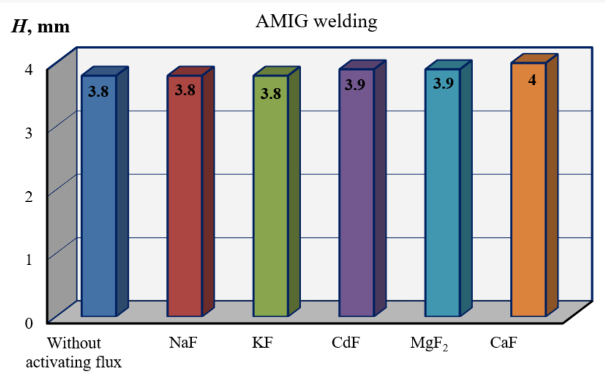
2 EXPERIMENTAL RESULTS AND ANALYSIS

The results of the research shown in Fig. 1 indicate that when welding carbon steel, fluorides, as components of activating fluxes agens, do not show significant influence on the penetration ability of the electric arc. During ATIG welding (Fig. 1a), penetration increases by about 12-20% relative to conventional TIG welding. In arc welding with a consumable electrode, the penetration difference between the conventional MIG method and the AMIG welding process is approximately 3-5% (Fig. 1b) and does not go out of the bounds of the statistical error of measurement.

The influence of fluoride on the penetration power of an electric arc increases significantly during arc welding of the corrosion-resistant steel of the martensitic structure X11H10M2T (GOST) (Fig. 2). Fluorides representing a component of activating fluxes for welding austenitic steels [9] such as 08X18H10 (GOST) (DIN X5CrNi1810), 08X18H10T (GOST) (DIN X10CrNiTi18-9) and 12X18H10T (GOST) (DIN X12CrNiTi18-9) (Table 1). The basis of activating fluxes for welding titanium and its alloys are fluorides [4,5].



a)



b)

Figure 1. Influence of fluoride on the penetration property of an electric arc during welding of carbon structural steel

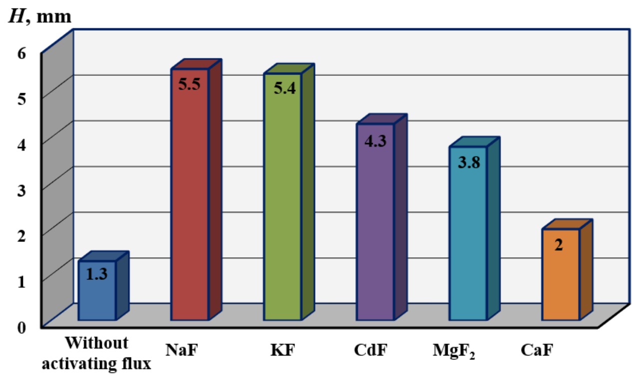


Figure 2. Influence of fluoride on the penetration property of an electric arc during ATIG welding steel of type X11H10M2T

Using activating fluxes containing 15-30% fluoride, for orbital welding of the pipes of steel 08X18H10T and 12X18H10T, as well as cylindrical high pressure tanks of steel 08X18H10 and 12X18H9T (Table 1), it is possible to increase the penetration of the electric arc up to twice and to obtain quality formed single-pass seam thickness up to 6 mm in all spatial positions. When adding fluoride to the activating fluxes for welding of ferritic-perlite steel pipes, Steel 20 (GOST) (DIN St35) don't influence by the increase in the penetration properties of the electric arc and the quality of the welded joint.

Table 1. Chemical composition of welded steels [10]

Steel	Chemical composition/ wt. %									
	C	Mo	Cr	Ni	Ti	Si	Mn	S	P	Cu
Corrosion-resistant steel high strength										
X11H10M2T	0.03	1.8	11.6	10.1	1.07	≤0.8	-	0.010	0.010	-
Austenite (corrosion-resistant) steels										
08X18H10T	≤0.08	-	17.0 -19.0	9.0 - 11.0	0.5 - 0.7	≤0.8	≤2.0	≤0.020	≤0.035	≤0.30
12X18H10T	≤0.12	-	17.0 -19.0	9.0 - 11.0	0.5 - 0.8	≤0.8	≤2.0	≤0.020	≤0.035	≤0.30
08X18H10	≤0.08	-	17.0 -19.0	9.0 - 11.0	≤0.5	≤0.8	≤0.2	≤0.020	≤0.035	≤0.30
12X18H9T	≤0.12	-	17.0 -19.0	8.0 - 9.5	0.5 - 0.8	≤0.8	≤2.0	≤0.020	≤0.035	≤0.30
Ferritic-perlite (carbone) stell										
Cтeel 20	0.17 - 0.24	-	≤0.25	≤0.25	-	0.17 - 0.37	0.35 - 0.65	≤0.04	≤0.035	≤0.25

Data (Fig. 2) show that the maximum depth of penetration of an arc at ATIG welding of steel type X11H10M2T is provided by fluorides with relatively low melting and evaporation temperature (Table 2), which do not exceed 1000°C and 1700°C respectively.

Table 2. Melting point and temperature evaporation some fluorides

Component of the chemical composition of the activating flux	Melting point, °C	Temperature evaporation, °C
KF	858	1502
NaF	993	1700
CdF	1072	1750
MgF_2	1263	2239
CaF	1418	2533

Fluorides very intensely affect the penetration of an electric arc during the welding of austenitic steels. When it comes to carbon steels, fluorides don't have any influence on the increase in penetration. If we compare the chemical composition of these steels (Table 1), we can conclude that the same can not be the reason for this phenomenon when it comes to carbon steels.

Corrosion-resistant steel X11H10M2T contains 0.01% of sulfur, and at the austenitic steel is allowed the max. of 0.02%. This is enough for a more intensive influence on the increase in the depth of melting of this material [11]. That is why the intensity of the influence of fluoride on the penetration ability of an electric arc on welding of carbon steel containing up to 0.04% sulfur and corrosion-resistant steels should be approximately equal. However, the results of the research say the opposite.

The influence of oxygen as an actuating fluxes admixture on the depth of penetration in welding corrosion-resistant steels is not manifested through a high degree of their deoxidation [12], as evidenced by their silicon content up to 0.8%, which allows the deoxidation of steel, already with its content 0.17-0.23%.

Explanation of the occurrence of a different degree of influence of fluoride on the penetration power of an electric arc during the welding of the mentioned steel grades enabled a comparative study of the energy capacity of the welding process, achieved on elements of thicknesses of 3.5 mm and 6 mm steel Steel 20 and 12X18H10T. Welded joints with a thickness of 3.5 mm were realized with and without the use of an activating flux, and the 6 mm were realized only using an activating flux. The drive energy (q/V) [13,14] required for the production of quality single-welded welded joints were compared. The results of the research are shown in Table 3. The data from the table show that at the thickness of the welded material 3.5 mm for full of penetration of austenitic steel with TIG, the driving energy required is 2 times smaller than for welding of ferritic-perlite steel Steel 20. For ATIG welding of these steels the same thickness, this relationship is retained.

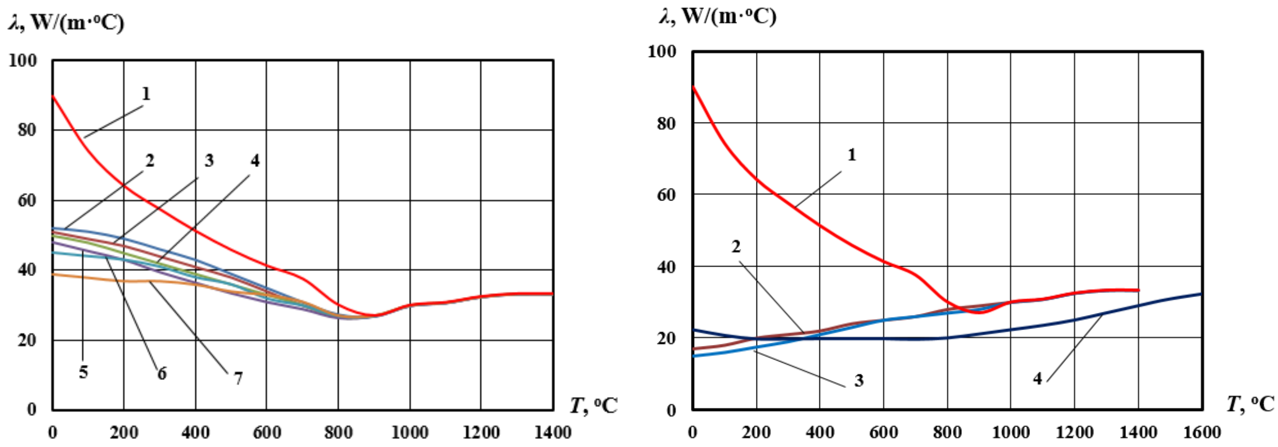
Increasing the thickness of the welded material up to 6 mm it is decreasing the difference between the welding drive energy of austenitic and ferritic-perlite steel, but it still exists and stands at 1.4 times. These a difference in the drive energy required for the full of penetration of austenitic and ferritic-perlite steel condition the difference in their thermal conductivity properties and the nature of her change in temperature dependence.

Table 3. Driving energy required for high-quality single-pass arc welding of ferritic-perlite and austenitic steel grades

δ / mm	q/V / J/cm			
	TIG		ATIG	
	Steel 20	12X18H10T	Steel 20	12X18H10T
3.5	8991	4194	6227	2741
6	-	-	9720	7020

On Fig. 3 shows the curves of the dependence of the thermal conductivity (λ) of iron, carbon steel (Fig. 3a) and austenitic steels (Fig. 3b). The curves were constructed using the method of interpolation and ex-polplication, based on data from earlier studies [10,15]. The chemical composition of corrosion-resistant and carbon steel is shown in Table 1 and Table 4. With increasing carbon content and alloying elements in carbon steel, their thermal conductivity decreases compared to pure iron 1.7-2.3 times (Fig. 3a). Also, the thermal conductivity decreases with increasing temperature to the level of austenite transformation temperature (Table 5). The thermal conductivity of pure iron and carbon steel reaches its maximum value in the austenitic state. With the further increase in the warming temperature, the carbon steels start behaving like pure iron. The influence of carbon and alloying elements on thermal conductivity its equalized. This condition is connected to the dissolution process in the austenitic of all the ingredients contained in the steel and the homogenization of the solid solution.

With the warming up of the material, the heat conductivity of austenitic steels and the character of its change are significantly different from iron and carbon steels. It is 5-6 times lower than with pure iron and 2.5-3.5 times lower than in analyzed carbon steels (Fig. 3b). Change in heat conductivity in addiction to temperature is different from its change in iron and carbon steels. With heating, the thermal conductivity of austenitic steels increases to the level of thermal conductivity of the iron in the austenitic state and reaches its maximum, which corresponds to the minimum thermal conductivity of iron and carbon steels.



Carbon steels: 1- iron (Fe);
2 – Steel 20; 3 – Steel 30; 4 – Steel 40;
5 – M72; 6 – 40XH; 7 – 30XГCA

a)

Corrosion-resistant steels and titan: 1- iron (Fe); 2 – 08X18H10; 3 – 08X18H10T, 12X18H10T, X11H10M2T; 4 – titan (Ti)

b)

Figure 3. Dependency the thermal conductivity (λ) from the chemical composition of steel and the temperature of its heating

Table 4. Chemical composition of carbon steels [10]

Steel	Chemical composition/ wt. %							
	C	Si	Mn	Cr	Ni	max.		
						Cu	S	P
Steel 20	0.17-0.24	0.17-0.37	0.35-0.65	≤ 0.25	≤ 0.25	0.25	0.04	0.035
Steel 30	0.27-0.35	0.17-0.37	0.50-0.80	≤ 0.25	≤ 0.25	0.25	0.04	0.035
Steel 40	0.32-0.40	0.17-0.37	0.50-0.80	≤ 0.25	≤ 0.25	0.25	0.04	0.035
M72	0.67-0.78	0.18-0.45	0.75-1.05	-	-	-	0.04	0.035
40XH	0.36-0.44	0.17-0.37	0.50-0.80	0.45-0.75	1.00-1.40	0.30	0.035	0.035
30XГCA	0.28-0.34	0.90-1.20	0.80-1.10	0.80-1.10	≤ 0.30	0.30	0.035	0.035

Table 5. The temperature of the start and end of the austenitic transformation [10]

Temperature, °C	Designation of steel						
	Fe	Steel 20	Steel 30	Steel 40	M72	40XH	30XГCA
Ac_1	911	735	730	730	730	735	760
Ac_3	911	850	820	790	743	768	830

According to these data - the heat transfer from the welding zone in the base material of austenitic steels is minimal. That is why, when obtaining welded joints of this class of steel, significantly lower heat input is required, i.e. smaller driving energy. By lower energy input, we create a condition that the power of an electric arc is smaller when welding austenitic steels, which makes it different from welding of carbon steel. This explains the high degree of efficiency of fluoride application at ATIG welding of austenitic steels compared to carbon steels for whose the welding requires input a significantly higher amount of heat, i.e., higher driving energy.

At the same time the previous ascertainment, confirms the high degree of effectiveness of fluoride compounds on the penetration properties of the electric arc during welding of titanium, whose thermal conductivity at temperatures exceeding 200°C is lower than with austenitic steels (Fig. 3b, curve 4). Conversely, the application of fluoride in the fluxes to welding copper, although there are research results [14], nevertheless wider development, as in welding of austenitic steels and titanium, it has not been achieved. Analog results were obtained during research at the E.O. Institute Paton (Ukraine) on the influence of fluoride on the penetration capability of an electric arc during the welding of aluminum and its alloys. It has been shown that fluorides do not substantially affect the increase in penetration of the electric arc. The explanation is found in the fact of the high thermal conductivity of copper and aluminum (Fig. 4). It is much higher than iron, carbon steels, and austenitic steel, and also titanium.

During welding aluminum, the very intensely influential effect on the penetration of the elastic arc has oxides. However, the mutual interaction of oxides and aluminum, as well as copper, makes the development of the fluxes in this direction more difficult.

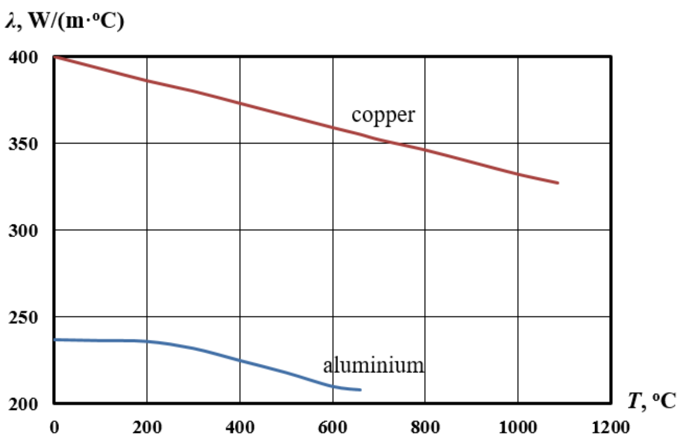


Figure 4. The dependence of thermal conductivity on the temperature of the heating

Application of fluoride in activating fluxes during welding austenitic steels, although in limited quantities (10-30%), is necessary due to the increased oxygen activity that very intensely oxidizes the metal seam.

It was determined that the effectiveness of the action of the activating fluxes on the penetration property of the electric arc depends only not on the chemical composition, but also on the thermophysical character of the welded material. The nature of their change depends on the temperature of the heating, and also the temperature resistance of the components of the activating fluxes.

Curves that are shown in Fig. 3 indicate that after completing the austenitic transformation process, iron and carbon alloyed and unalloyed steels are characterized by minimal thermal conductivity. Metal in an austenitic state represents a barrier on the way of spreading heat from the zone more to the zone of lower heating. In a welded joint, the function of the thermal barrier has a small part of the metal, whose initial structure is subjected to process austenitization [17]. This part of the metal represents the segment of the overheated zone heat-affected zone (HAZ) that directly surrounds the liquid bath of the weld and prevents the heat transfer from it to the base metal.

In the heating phase, the heat barrier has a positive influence on the formation of the welded joint, reduces the intensive heat removal from the welding zone and helps to centralize the heating and form the bath weld. In the cooling phase, everything is changing - the heat barrier prevents the heat from being removed from the bath cheese in the base metal. This phenomenon contributes to the increase in the bath residence interval in the temperature interval of crystallization [18]. The likelihood of the formation of hot cracks in the seam metal is increased. Thanks to the combination of minimum thermal conductivity and high-temperature capacity [10], the heat barrier is able to accumulate a significant amount of heat and retain it for some time.

All these factors conditioned the development of the process, and contribute to the formation of hot and cold cracks, as well as the formation of a coarse grain structure of the welded joint [19].

3 CONCLUSION

The results of the test show that the quality of welded joints, the conditions of their forming, welding regimes and the chemical composition of activating fluxes depend directly on the thermophysical state of the welded materials and the character of their changes in the processes of heating and cooling.

The negative impact of the thermal barrier on the weldability of carbon steels increases with increasing her dimensions and the time of her existence.

The results of the research show that the thermal barrier in welded carbon steels compounds are physical and objective phenomenons. It is impossible to prevent its formation in the modern stage of technical development. In addition, in the heating phase, the thermal barrier has a positive effect. That is why methods that allow control of geometry, limit and reduce the negative influence on the formation of welded joints are necessary.

The dimensions and the interval of the existence of a heat barrier depend on the heat input in the metal during welding and increases with increasing welding power [17,19]. Therefore, in order to reduce the negative impact of the thermal barrier on the formation of welded joints, it is necessary to reduce the energy of the welding. Also, focus on welding processes with low energy intensity and high concentration of heating, just like it is common for arc welding in a protective atmosphere using activating fluxes [1,2].

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