DETACHABILITY OF SLAG CRUST IN ARC WELDING (Review)
Part 2. Character of the effect of main factors on detachability of slag crust*

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The effect of various particular factors on detachability of slag crust in automatic arc welding is analysed. It has been established that the flux being developed for narrow-gap automatic arc welding of thick joints should ensure formation of the slag crust with the minimum possible strength and maximum possible linear thermal expansion coefficient. Brief characterisation of the currently available methods for experimental evaluation of detachability of the slag crust is given.

Keywords: *submerged arc welding, multipass welding, narrow gap, alloyed steels, slag crust, detachability, chemical adhesion, phase composition of slag, oxidation potential*

Problems associated with removal of slag crust in narrow-gap welding of thick-walled butt joints on alloyed steels are caused by chemical adhesion of slag to the weld metal and mechanical fixation of the crust. The mechanism of chemical adhesion was formulated in Part 1 of this study [1].

Mechanical fixation of the crust on the surface of a welded joint may take place independently of the presence or absence of chemical adhesion. In some cases such geometric peculiarities of the metal surface as depressions may be filled up with a liquid slag, which solidifies in cooling, thus leading to mechanical jamming of the crust when it is removed. This can be caused by violations of the welding technology resulting in formation of such defects as lacks of fusion, undercuts, and coarse ripples on the weld surface. However, in many cases the conditions that cause mechanical fixation of the crust may result from edge preparation even with a strict adherence to the welding technology. During groove filling, the edges of the pieces welded approach each other (the groove becomes narrower), this causing fixation and compression of the slag crust in the groove. The latter is likely to take place if approaching of the edges exceeds the value of transverse reduction of the slag crust.

The welding process is characterised by many particular factors that affect completeness of occurrence of both mechanisms causing deterioration of detachability of the slag crust (chemical adhesion and mechanical fixation). Knowledge of the role and character of the effect of the above factors on detachability of the slag crust is very important for development of a flux for multipass narrow-gap welding of alloyed steels. In this connection, it is of interest to analyse the available applied research results on the effect of the most important factors on detachability of the slag crust.

Detachability of the slag crust can be affected to a substantial degree by varying the welding process parameters. Increase in heat input during welding of low-carbon steel leads to increase in time of contact of the softened slag and solidified weld metal. This results in growth of thickness of the oxide interlayer and deterioration of detachability of the slag crust. Decrease in arc voltage causes decrease in the amount of the molten slag and favours improvement of detachability of the slag crust [2]. However, the technology for welding of low-alloy limited-weldability steels stipulates for a wide-range variation of the process parameters, as well as for concurrent heating. In this connection, in welding of the given steels the above regularities are of low practical significance.

Correlation was revealed between the character of detachability of the slag crust, adhesion W and surface tension σ_{m-s} at the metal–slag interface [3]. It was experimentally proved that deterioration of detachability of the slag crust is accompanied by decrease in inter-phase tension at the interface between the slag and metal, which corresponds to increase in wettability of metal with the slag and intensification of the oxidation-reduction processes at the metal–slag interface [4]. In this case, the value of adhesion calculated from the Dupre formula increases:

$$W = \sigma_m + \sigma_s - \sigma_{m-s},$$

where σ_m (σ_s) is the surface tension of metal (slag) at the interface with the environment.

It was established that detachability of the slag crust at $W > 9\cdot10^{-3}$ N/cm is unsatisfactory independently of the proportion of the slag and deposited metal, and at $W < 9\cdot10^{-3}$ N/cm the lower the value of W, the better is the detachability.

*Beginning of the article is given in TPWJ, 2011, No. 1.

Much experimental data on the relationship of linear thermal expansion coefficient (LTEC) of slag α_s and metal α_m have been accumulated, but the conclusions made by different researchers are contradictory.

For instance, the authors of studies [5, 6] are of the opinion that the slag crust can be most readily removed from the groove at $\alpha_s > \alpha_m$. At $\alpha_s = \alpha_m$ the crust is not jammed, but some deterioration of its detachability might be expected. At $\alpha_s < \alpha_m$, the higher the difference of $\alpha_s - \alpha_m$, the more difficult it is to remove the crust from the groove. LTEC of slags, like of other oxide systems, depends on the chemical composition and may vary over very wide ranges [5, 6]. However, there is an opposite opinion that an easy detachability of the slag crust can be achieved if $\alpha_s < \alpha_m$. This statement can be found in many papers with a reference to study [7], where detachability of the slag crust formed in manual deposition of beads on steel plates by using electrodes VSR-50 manufactured by several factories was determined experimentally. In each case the volume thermal expansion coefficients (VTEC) of the slag crust were measured, among other parameters. And it was established that the electrodes with a better detachability of the slag crust had a lower value of VTEC than the electrodes with a worse detachability.

Proceeding from the simplified mechanism of fixation of the slag crust in the groove on the basis of the α_s and α_m relationship, study [6] expresses doubts about the results obtained in [7]. Moreover, it ignores the substantial differences in the procedure used by the authors of study [7] to determine detachability of the slag crust. Nevertheless, investigation of the combined cooling of the slag crust and plate with the deposited bead suggests that the conclusion of study [7] is correct.

Also, there is an opinion that in terms of detachability of the slag crust the absolute difference of $\alpha_s - \alpha_m$ is important, rather than the relationships of the type of $\alpha_s \geq \alpha_m$ or $\alpha_s < \alpha_m$. The higher the value of $|\alpha_s - \alpha_m|$, the better is the detachability of the slag crust, other conditions being equal. Based on the hypothesis of a local fixation of slag, the authors of study [8] see this effect of LTEC in the presence of chemical adhesion of the slag to metal «rooted» into the grain boundaries. Increase in $|\alpha_s - \alpha_m|$ leads to growth of tangential stresses at the slag to metal interface in cooling, which promotes fracture of the grain-boundary connecting «links» between the slag and metal.

Investigations were conducted to closely study polymorphic transformation of dicalcium silicate, and its realisation with a positive result was tested in practice of manufacture of covered electrodes [9–11]. It is a known fact that in cooling of dicalcium silicate $2CaO \cdot SiO_2$ its high-temperature β-modification with a density of 3.10–3.28 g/cm^3 transforms into a low-temperature γ-modification with a density of 2.80–2.97 g/cm^3. The transformation has no definite starting temperature. It may occur at a temperature from 1000 °C to room temperature, depending on the conditions. The resulting increase of up to 12 % in the specific volume of slag and internal stresses in them leads to self-grinding (self-spilling) of the slag, which has a very favourable effect on its removal from the groove.

Based on the stoichiometric proportion of oxides in structure of $2CaO \cdot SiO_2$, the authors of studies [9, 12] believe that the necessary condition for formation of this silicate in slag is the proportion of the $CaO:SiO_2$ molar fractions close to 2, or the weight fraction proportion close to 1.87, or $CaCO_3:SiO_2 = 3.33$. In practice, the lower limit of the $CaO:SiO_2$ proportion, at which $2CaO \cdot SiO_2$ can be detected in slag by X-ray diffraction analysis and improvement of detachability of the slag crust is observed, can amount to 0.5.

Study [13] describes the polymorphic transformation occurring at T = 800–650 °C in slags of the $MgO-SiO_2-BaO-Al_2O_3$ system, which is accompanied by increase in the specific volume without self-spilling of the slag. In this case, the polymorphic transformation plays a negative role in detachability of the slag crust.

An addition of 15 wt.% ZrO_2 to the oxide-fluoride slag system allows a substantial improvement of detachability of the slag crust in welding with self-shielding flux-cored wires [14]. Zirconium dioxide forms an independent crystalline phase of ZrO_2 in slag, in addition to calcium zirconate $CaO \cdot ZrO_2$. Cooling involves a number of polymorphic transformations of ZrO_2 with a marked change in the specific volume of the newly formed phases, this positively affecting detachability of the slag crust.

Therefore, the polymorphic transformations of slag accompanied by a change in the specific volume may have both positive and negative effect on detachability of the slag crust.

An important factor of detachability of the slag crust is its strength. As follows from the above regularities, it plays an ambiguous role, and its role depends on the type of a welded joint and presence of chemical adhesion between the slag and metal. Low mechanical strength of the slag promotes an easier removal of the slag crust jammed in the groove at the presence or absence of chemical adhesion, as well as from the surface of the bead deposited on a plate at the absence of chemical adhesion. High mechanical strength of the slag crust, as believed by the authors of study [8], provides its easier removal from the surface of the deposited bead at the presence of chemical adhesion.

The factors of strength of multi-phase systems of partially solidified or mainly crystalline slags are proportions of crystalline and amorphous components [2], as well as types and sizes of crystals. It might be expected that decrease in strength of the slag crust will be favoured primarily by the phenomena that lead to formation of structural stresses and microdefects in it, such as anisotropy of thermal expansion of crystals, difference in LTEC between the glass phase and adjacent crystals and between separate crystals, susceptibility of crystals to polymorphic transformations with a change in their specific volume, etc. The degree of compactness of the slag crust also has a marked effect on its strength [15]. A spherical pore formed in a material acts as a mechanical stress raiser, and the smaller the radius of the pore, the stronger is its effect. According to the calculations [16], the 10 % porosity decreases strength of the material approximately two times, compared to the solid material.

Detachability of the slag crust is a very complicated process, the character of which depends on many phenomena of a physical-chemical and physical-mechanical nature. In this connection, the general physical investigation methods are applied to study problems of detachability of the slag crust. For example, to investigate slag in terms of its structural-size correspondence to the weld metal and oxides, in a general case it is necessary to determine chemical composition of metal, identify crystalline phases in the metal, its oxides and slags, and determine type and parameters of their crystalline lattice. The chemical, spectral, X-ray diffraction and X-ray microprobe analysis methods are employed for these purposes. Phase (mineralogical) composition of slags is also investigated by the crystal optics and petrography methods. The presence and temperature of occurrence of polymorphic transformations in slags with a change in their specific volume are established, and LTEC values of the slags are determined by using the dilatometry methods.

As noted above, strength of the slag crust is an important factor in terms of its effect on detachability. Strength of the slag crust can be predicted from the results of identification of the slag phases. However, of a higher interest is its direct quantitative evaluation. The procedure of determination of strength of the slag crust is used for this purpose [14].

Methods for direct experimental determination of detachability of the slag crust have the following sequence: realisation (simulation) of the investigated variant of welding with participation of the metal and slag phases; removal of the slag crust by the procedure that involves the force impacts on it as a physical experiment with a simultaneous measurement of parameters and results of these impacts, or as a technological test with a statement of qualitative attributes. These methods allow a direct determination of detachability of the slag crust as a result of the additive effect of a set of factors characteristic of the selected technological variant of welding.

As the manual slag crust removal method is most widely applied in the welding industry, the first notions of the character of detachability of the slag crust were, undoubtedly, of the organoleptic origin, and specialists considered this property of the slags to be qualitative. The qualitative (point-rank) method for evaluation of detachability of the slag crust in welding consists in the fact that performer of the slag crust removal operation forms its own opinion on the detachability proceeding from the results of his direct actions. Determination of the detachability at the qualitative level is more preferable for production, as it is not time-consuming and requires no special tools. Also, this method is very often used in theoretical studies [1, 2, 6, 12–15, 17].

When solving the problems of detachability of the slag crust, it is desirable to have the possibility of quantifying it at the scientific-and-technical level. One of such methods [18] is based on the fact that V-groove welding is performed on a plate of the investigated base metal by using the investigated welding consumables. Upon cooling a sample to room temperature, the angle between the groove edges is gradually increased by three-point bending under static loading until the slag is detached. The authors of study [18] take angle γ of bending of the plate equal to increase in an angle between the V-groove edges at which the slag is detached as a measure of detachability of the slag crust.

Other methods were suggested later on, where the energy of various dynamic loads transferred to the welded joint or slag crust to remove it from a unit surface of metal was used as a measure of detachability of the slag crust. Detachability of the slag crust in this case is measured in Joules per square meter or square meters per Joule.

Such a method was first proposed by I.N. Vornovitsky and co-authors [19, 20]. Thereafter it received acceptance in practical studies [9, 21, 22]. According to this method, an experimental sample with a deposited bead in the V-groove and non-removed slag was put on supports of the impact pendulum-type testing machine. The rear plane of the sample was impacted by a weight suspended on the pendulum. Energy E transferred to the experimental sample as a whole was metered by varying mass and height of lifting of the weight. The E/F ratio was calculated by measuring area F of the weld metal cleared from the slag as a result of the impact.

The method described in study [23] is based on the principle of removal of the slag crust by the inertia force. According to this method, a stop of the sample moving at speed v because of impact collision with a fixed arrester causes removal of the slag with mass M from some surface of a spot weld with area S under the slag inertia forces. Division of its kinetic energy accumulated before the stop by surface area S gives the value of the specific energy of detachability of the slag crust. A drawback of the method is that preparation of the sample is not related to the welding technology. This makes it necessary to study the issue of the effect by the weld deposition conditions on detachability of the slag crust, as this property may depend, in particular, on the heat input, time of existence of the slag pool, etc. [1].

The common drawback of the methods for determination of detachability of the slag crust [20, 23] and method for evaluation of strength of the slag crust [5] is that it is necessary to establish the minimal value of the force effect sufficient for obtaining the planned experimental result. The minimal value of the energy can be correctly determined by the said methods only by way of multiple reiteration of the experiment, where the energy of the force effect gradually changes, the other factors remaining unchanged. For this it is necessary to prepare several, nominally identical experimental samples, which makes the investigations more time- and materials-consuming.

Therefore, development of the new methods for quantitative evaluation of detachability of the slag crust (as well as for improvement of the available ones) should be regarded as a topical problem for specialists in the field of welding.

CONCLUSIONS

1. In welding of alloyed steels, the possibilities of improvement of detachability of the slag crust through varying the welding process parameters are limited.

2. To improve detachability of the slag crust, the composition of flux for welding of thick-walled joints on alloyed steels should be selected so that it could provide the slag crust with a maximum possible LTEC and minimum possible strength.

3. Strength of the slag crust can be changed, and its detachability can be improved by providing a target effect on peculiarities of its micro- and macrostructure, in particular, due to the presence of the phases susceptible to polymorphic transformations, which leads to self-spilling of the slag.

4. The majority of the available methods for direct experimental determination of detachability of the slag crust are characterised by increased time and materials intensity, this hampering their wide application. Development of the methods for quantitative determination of detachability of the slag crust in welding is still a topical problem. At present, the qualitative method for evaluating it on bead-on-plate samples is most common.

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