THE NATURE OF NONMETALLIC INCLUSION DISTRIBUTION IN THE WELD METAL STRUCTURAL COMPONENTS AT ARC WELDING METHODS

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With the purpose of expert evaluation of welded joint performance a large number of computer programs have been developed now for prediction of the weld metal structural composition and their mechanical properties. Such programs are usually based on multivariate analysis of the processes occurring in the welding arc, and thermodynamics and kinetics of the processes in the weld pool. It should be noted that at analysis of crystallization and recrystallization reactions in the weld metal, such programs usually do not take into account the nature of nonmetallic inclusion distribution in the structural components. There are many studies, which point to a significant impact of the inclusion, depending on whether they are present on the boundaries or in the body of the grains. The paper shows the need to take into account the probability of nonmetallic inclusions being in the body of structure grains or on their boundaries at construction of the numerical models that will allow improving the correspondence of the predicted data and the experimental results of determination of the mechanical characteristics of weld metal. 5 Ref., 5 Figures.

K e y w o r d s : metals science, low-alloy steels, welds, microstructure, numerical modeling, nonmetallic inclusions

The impact of nonmetallic inclusions on the structure and properties of welds on iron alloys has been given a lot of attention already for about one and a half centuries. It should be noted that this problem remains relevant over time, and this is related to the change of ideas about the peculiarities of their impact. While the first works provided convincing proof of the negative effect of increased volume fraction of inclusions in welds on formation of metal mechanical properties, lateron the researchers found that the size distribution and chemical composition of the inclusions should be taken into account. At the end of the XX century studies were performed, which demonstrated the positive role of certain inclusions in the processes of secondary crystallization of low-alloy steel welds. In studies conducted in recent years, attention was paid to the impact of nanosized inclusions on increasing the level of mechanical properties of welds of high-strength low-alloy steels. Proceeding from the results of scientific research, laboratory testing and industrial practices, one can come to the conclusion that analysis of the impact of nonmetallic inclusions on the structure and properties of welds requires application of a complex approach, which allows not only for the topological indices, but also for the physicochemical characteristics of both the inclusions proper, and the nature of their interaction with the metal solution and the crystalline phase. Here, it was noted more than once that the inclusions impact depends on where exactly they are located: in the center of large grains or on the intergrain or intragrain boundaries. However, while a large scope of research was devoted to the issues of inclusion distribution in welds by size and chemical composition, their impact on formation of the structure and mechanical properties of weld metal, the problem of distribution of inclusions in the microstructural components is given much less attention.

The problem of modeling the processes, which affect formation of weld microstructure, in order to predict the level of its performance, requires conducting multivariate analysis. Modern possibilities of computer processing of large data bases, and numerical analysis of thermodynamics and kinetics of nonequilibrium processes enable solving such tasks. Over the past decade, there were publications, in which the authors show the ability of such an approach to solve the complex problem with optimization of the technology of welded metal structure fabrication, for instance [1–5]. The role of nonmetallic inclusions is taken into account in these works, in terms of their distribution by size and chemical composition. However, the nature of inclusion distribution in the structural components proper is ignored. In our opinion, modeling of the impact of nonmetallic inclusions without allowing for the nature of their distribution in the structural components will not enable sufficiently reliable prediction of the mechanical properties of weld metal.

The work gives an idea about the processes, which determine the nature of distribution of nonmetallic inclusions in the microstructure of metal of low-alloy steel welds.

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Inclusion formation. Most of the welding processes are accompanied by melting of the base and filler metal simultaneously with slag-forming material in the form of electrode coating, flux-cored wire core, or welding flux. High energy concentration between the melting electrode and weld pool promotes formation of a plasma discharge of up to 20000 K temperature, in which the welding wire and the flux melt, evaporate and decompose into constituent elements. These elements are transferred from the electrode into the weld pool by three main methods (Figure 1):

● as ions in the plasma column;

● as fine drops on the plasma periphery;

● as large drops, which separate from the electrode tip and are transported through the plasma during a brief time period.

In addition, loss of certain elements occurs through evaporation in the welding arc atmosphere.

Welding process parameters have a strong impact on arcing stability, effectiveness and mode of element transfer into the weld pool. Therefore, despite, for instance, the fact that the flux almost entirely consists of oxides and fluorides, they are not transferred through the arc in the form of the initial compounds at all, but rather as constituent elements. Only rather coarse particles of the electrode coating, which are capable of remaining unchanged while passing through the welding arc, can penetrate into the weld pool and significantly impair the mechanical properties of weld metal. The weld pool cast metal ($T > 2600$ °C) contains alloying elements (Ti, Al, Si, Mn, etc.), which passed from the welding material and base metal, and a large amount of oxygen, as its solubility in liquid alloys of iron with carbon is high (0.22–0.29 % in iron melting point) and rises (up to 0.33 %) at 1700 °C.

Oxygen comes from the ambient atmosphere or from the shielding gas, which often has CO_2 in its composition. This process should be controlled, as oxygen content in metal drops at the electrode tip can be up to 5000 ppm, and this requires a large amount of deoxidizers for oxygen removal from the weld pool at its cooling. In addition, presence of oxides in the flux, which readily decompose (SiO_2 type), leads to increase of oxygen content in the weld metal, which enters it from the slag. Increase of the content of higher basicity compounds (CaO, MgO and CaF_2) in the flux promotes reduction of the amount of oxygen in the weld, although oxygen potential and basicity are not necessarily connected. In welding using highly basic fluxes, oxygen content can be lowered to the level below 200 ppm, but this necessitates application of such strong deoxidizers as aluminium. Depending on their tendency to oxidize, the oxides can be arranged in a certain sequence, and oxygen potential can be deter-
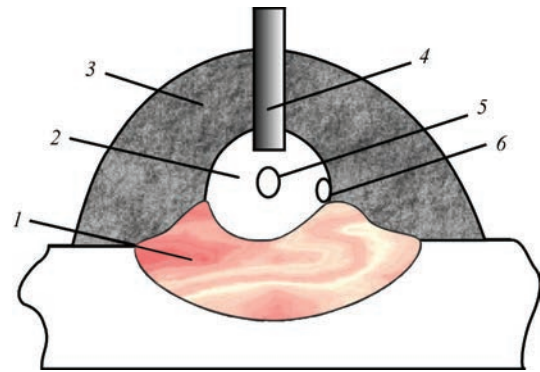

Figure 1. Main modes of chemical element transfer in the welding arc: *1* — weld pool; *2* — plasma; *3* — flux; *4* — electrode; *5* — large drops in arc column; *6* — drops on the periphery

mined based on partial pressure of oxygen, which is found from the decomposition energy of pure oxides. The oxides were arranged in the direction of lowering of their tendency to decompose, in the following order: $SiO_2 > TiO_2 > Al_2O_3 > ZrO_2$.

In arc welding methods with slag phase participation, oxygen transfer is determined by the conditions of FeO formation in the slag, as a result of flux oxide decomposition. The amount of FeO which enters the weld pool, increases with reduction of free energy of flux oxide formation, so that MnO, SiO_2 and Cr_2O_3 essentially affect weld metal oxidation. In most cases, however, up to 90 % FeO is removed from weld pool metal into the slag.

Oxygen solubility in iron drops abruptly with temperature lowering (at 1345 °C oxygen solubility in γ-iron is equal to 0.003–0.007 wt.%), here the driving force of oxide formation becomes greater. This results in appearance ahead of crystallization front, of predominantly oxide particles with a higher temperature of formation, i.e. it can be assumed that refractory oxides, based on Al, Si and Ti form in the metal melt in a homogeneous manner. Such conditions of inclusion formation can be predicted, proceeding from Ellingham diagram (Figure 2).

Processes, controlling inclusion distribution in weld metal structure. The strongest oxides are located in the lower part of the diagram and form at a lower activity of oxygen, assuming that its activity is constant over the entire metal volume. Silicates form at much lower temperatures, than do oxides. On the whole, it is real to assume that they form during the process of metal solidification in interdendritic spaces which are enriched with impurity and alloying elements. This process can be promoted by presence of primary high-temperature oxides. Such a conclusion is confirmed by the nature of location of inclusions in interdendritic spaces (Figure 3).

The resultant complex of inclusions is determined by the time of segregation action and of inclusions growth, so that in the general case the oxides should
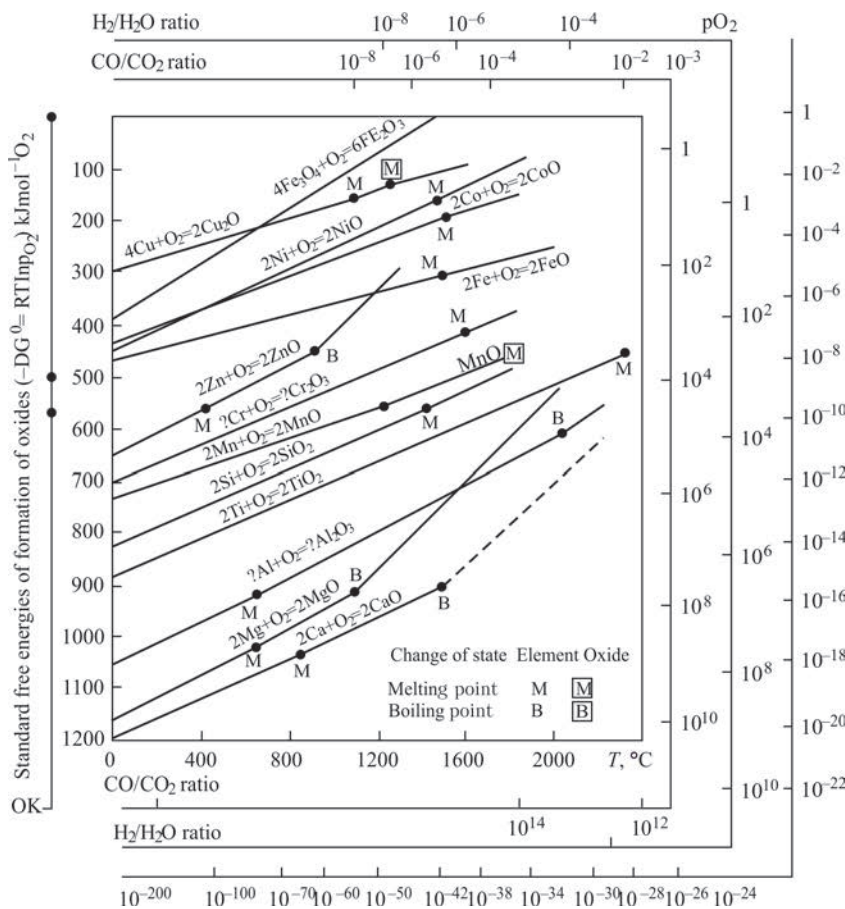
Figure 2. Ellingham diagram of the change in free energy of oxide formation

be larger (> 1 μm) than the silicates, as they are able to grow for a longer time. However, as the oxides form in a melt with high flow velocities and turbulence, a certain part of them is removed into the slag, others can be carried to the high-temperature zone of the melt, where their dissociation takes place. The process of separation of nonmetallic inclusions from the weld pool does not reach its completion, as certain particles are entrained by the solidifying metal front, thus forming an inclusion population in it.

Stokes law, that is flotation and separation as a result of the impact of the lifting force, does not apply to inclusions in the weld pool metal, because of insufficient time of the action of this force, and also because the metal flows have a much stronger effect. Two regions can be singled out in the weld pool by the intensity of these flows (Figure 4). The «hot» region with very turbulent metal flow, from which the particles are rapidly removed, and the «cold» one, located closer to the pool edges, in which the velocity of flow movement is much lower that leads to entrainment of a larger quantity of particles by the moving crystallization front. This explains why oxygen content in the deposited metal is usually higher than can be anticipated, proceeding from the conditions of thermodynamic equilibrium, approximated to the region of temperatures below the solidification temperature. In
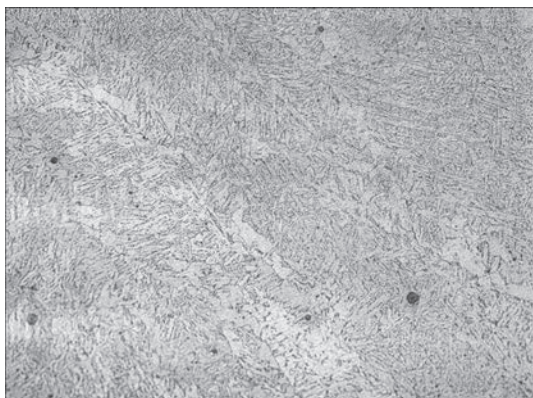

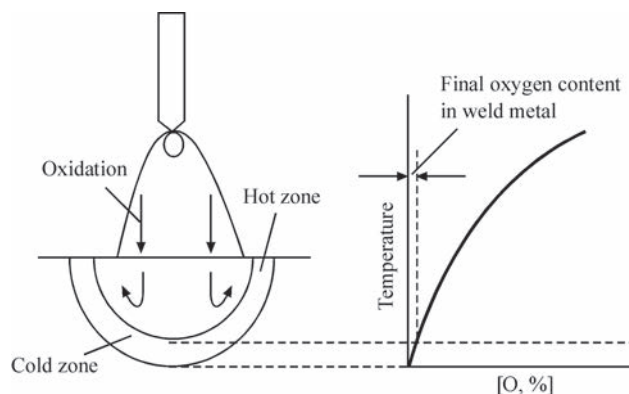**Figure 3.** Precipitates of coarse nonmetallic inclusions in the grain body (×200)
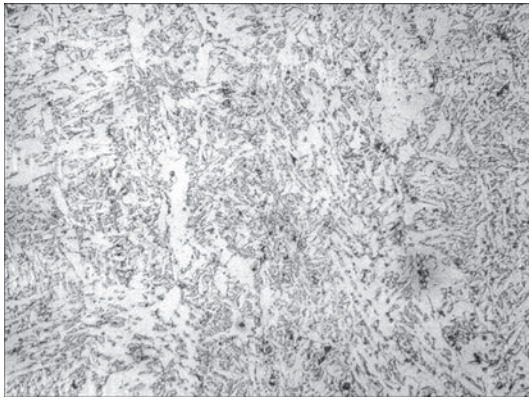

Figure 4. «Hot» and «cold» zones of the weld pool

Figure 5. Precipitation of silicate inclusions in the form of chains on grain boundaries (×500)

addition, Ellingham diagram applies only to spherical oxides, and gives the standard energy of their formation, referred to one mole of oxygen at this temperature, although high-temperature inclusions can have such carbides and nitrides in their composition with high melting temperature as, for instance TiN.

Interaction of the crystallization front with the inclusions, causes segregation of solid products of deoxidation, associated with segregation of alloying elements. Crystallizaton front advance can have such an impact on the inclusion, which makes it move forward, ahead of the crystallization front. Other mechanisms of impact can be also manifested, of the type of Marangoni effect, which is the result of the change in interphase tension. The effect of the last type depends essentially on melt composition, as segregation occurring on the crystallization front during the solid-phase growth, is caused by gradients of concentration and interphase tension, which lead to convection, directed towards the solidification boundary. Moreover, surface tension can cause nonuniform distribution of oxide particles. Coarse inclusions are characterized by low mobility, and that is why they are entrapped by the solidifying solution, while finer inclusions accumulate on the interphase front and are distributed along the grain boundaries.

The impact of any forces arising as a result of processes taking place in the melt flows, is proportional to the area of its contact with the inclusion, (r^2 for spherical inclusions), while the particle inertia is proportional to the volume (r^3 for spherical particle). Therefore, the segregation tendency should decrease with increase of the volume/surface ratio at increase of the spherical particle radius. Such dependence can be violated by the effect of particle floating, however, such an effect has not been detected up to now. Silicates, which form later, have a tendency to create a chain of inclusions along the interdentritic boundaries (Figure 5).

Experimental verification of such a nature of segregation is difficult, as the metal structure undergoes transformations during weld cooling, which violate the primary crystallization structure. Application of special etching methods that allow detecting the primary structure boundaries, allows establishing a correspondence between them and inclusion distribution. During weld metal cooling, further growth of inclusions, often in the form of sulphides, takes place, they often precipitating on the already existing inclusions. Many researchers noted the presence of Cu_xS film, which covers the oxide particles in the metal of welds of low-alloy steels. Increase of sulphur content in the weld metal leads to replacement of compounds rich in titanium oxide, by a film of (Cu, Mn) S type in the surface layer of the inclusions.

Conclusions

Reliable prediction of the structural composition of the metal of welds and their mechanical properties based on multivariate analysis is impossible without application of numerical modeling. With this purpose, researchers developed computer programs, which allow taking into account both the chemical composition of the base metal and welding consumables, and the parameters of welding technology. Application of such programs demonstrated the possibility of greatly increasing the effectiveness of such research developments in the field of fabrication of welded metal structures, on the one hand, and it also showed the presence of a noticeable discrepancy between the calculated data and experimental results in certain situations, which can be related to insufficiently full description of the features of formation of weld metal structure. The work gives an idea on the processes which determine the nature of nonmetallic inclusion distribution in metal microstructure of low-alloy steel welds.

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