Physical modelling of additives dissolution features in the bath of an induction furnace crucible

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The technology of melting metals in an induction furnace allows the production of a wide range of alloyed steels to meet the different needs of society and is more environmentally friendly as it produces fewer emissions. A special interest for modern metallurgy are the processes of alloying and deoxidizing, which occur directly in the induction furnace by introducing lump additives. In this work, the investigation of the process of melting of additives during induction melting has been studied in order to determine the optimal modes of introduction of deoxidizing and alloying additives into the melt, providing their maximum assimilation by the liquid metal. The study was carried out on the physical model simulating the crucible of a laboratory induction furnace equipped with a closed system of hydrodynamic circulation of liquid. The results demonstrate that the most rational place for the introduction of ferroalloys into the induction furnace crucible is the area of the melt located at a distance of 1/2 radius from the center of the crucible. There is also a tendency for the dissolution time to decrease as the depth of introduction into the melt increases. Considering that in practical industrial conditions, it is extremely difficult to organize the introduction of deoxidizing and alloying agents into the volume of metal melt, the necessity of holding the melt when introducing ferroalloy is reasonable.

KEYWORDS: INDUCTION FURNACE, ALLOY STEEL; FERROALLOY, DISSOLUTION TIME, STIRRING SPEED, PHYSICAL MODELLING

INTRODUCTION

The technology of melting metallic melts in an induction furnace has been known for over 100 years [1]. This enables to obtain both alloyed steel grades for the needs of mechanical engineering and special high-quality alloys, which is due to the high yield of obtaining molten steel (98-99%) and the ability to achieve and maintain the required composition in induction crucible melting [2]. In addition, the melting process in induction furnaces is more environmentally friendly, producing fewer vapors and smoke.

The alloying and refining processes carried out directly in the working chamber of the induction furnace through the addition of solid additives are of particular interest to modern metallurgy.

The analysis of the existing publications on the study of melting processes in an induction furnace mostly involves mathematical modelling of various aspects of this process. For instance, publications [3-7] provide a mathematical description of electromagnetic

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and thermodynamic phenomena. In works [8, 9], a computational mathematical analysis of the influence of turbulence on the processes in the induction furnace is conducted. A method for calculating the melting rate of the charge based on mathematical modelling is proposed in [10, 11]. By the use of a physical model, the present study aims to investigate the melting process of additives during induction melting to determine the optimal conditions for introducing refining and alloying agents into the melt, ensuring their maximum assimilation by the molten metal.

MATERIAL AND METHODS

The research was conducted via methods of physical modelling based on the use of low temperature melting materials [12, 13]. It considered the features of molten metal movement in the crucible through the combined action of electromagnetic and gravitational stirring. A specially designed laboratory set-up was developed, simulating the crucible of a laboratory-scale induction furnace with a capacity of 10 kg on a 1:1 scale (see Figure 1).

The experimental set-up consists of a transparent model of a 10 kg induction furnace crucible, a hydrodynamic circulation system (a pump with adjustable rotation speed and a system of branched pipes for the supply and discharge of liquid), a thermocouple to control the temperature of the liquid, a lighting system based on a solid-state light source with a brightness of 10000 lm, and a video recording system. The hydrodynamic fluid circulation system allowed the creation of hydrodynamic conditions inside the crucible model that corresponded to the real processes during the central lifting of the metal (along the vertical axis of the crucible). In this configuration, the design of the liquid inlet and outlet tubes ensured the formation of a complete circulation circuit directly within the crucible volume.

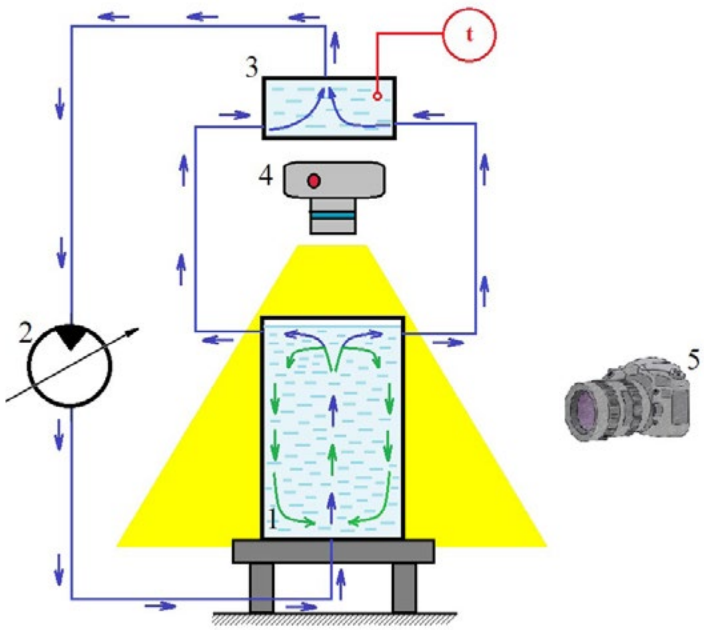

Fig.1 - Scheme of the experimental set-up for the simulation of hydrodynamic processes in the crucible of a 10 kg laboratory-scale induction furnace: 1 - transparent model of a 10 kg induction furnace crucible on a 1:1 scale; 2 - pump with adjustable rotation speed; 3 - distributor tank for organizing the hydrodynamic flow; 4 - solid-state light source; 5 - photo camera.

The assimilation process of the deoxidizer (alloying agent) is highly complex and can be roughly divided into dissolution, melting and distribution processes within the melt volume. Therefore, criteria of physical similarity were applied to maintain correspondence between the conditions of low-temperature modelling and those occurring during deoxidation and alloying in the 10 kg crucible of the laboratory furnace. In particular, thermal

similarity conditions were satisfied for the Nusselt number (Nu); it was necessary to maintain the Weber number (We) for dynamic similarity of fluid flows; for an accurate description of the stirring process, modified Euler (Eu), Reynolds (Re) and Froude (Fr) criteria were applied [14, 15]. The ratio of the density and melting temperatures of the molten metal and the alloying additive achieves compliance with these criteria. The average density and melting temperatures of deoxidizers and alloying additions used in the production of alloyed steels were taken from the study reported in [16].
Considering the availability of the source materials and the specificities of performing low-temperature modelling, water was chosen as the substance to simulate liquid steel and ice coloured with a green food dye (15 ml water and 0.07 g dye) to simulate ferroalloys. The comparison of the main physical parameters of the substances in the model and the model systems is presented in Table 1.

Tab.1 -Basic physical parameters of substances in the model and real systems.

Model System		**Real System**	
Density of water, kg/m3	997	Density of liquid steel, kg/m3	7000
Density of ice, kg/m3	916	Ferroalloy density*, kg/m3	6970 - 6372
Melting point of ice, °C	0	Melting point of ferroalloy*, °C	1450 - 1500
Temperature of water, °C	25	Temperature of liquid steel, °C	1550 - 1650
Thermal conductivity of ice, W/(m·K)	2.22	Thermal conductivity of ferroalloy, W/(m·K)	20 - 24
Thermal conductivity of water, W/(m·K)	0.57	Thermal conductivity of liquid steel, W/(m·K)	46.5
Specific heat capacity of ice, J/(kg·K)	2140	Specific heat capacity of a solid ferroalloy, J/(kg·K)	460
Specific heat capacity of water, J/(kg·K)	4180	Specific heat capacity of liquid steel, J/(kg·K)	840

* - averaged data from [16].

Considering that the difference between the melting temperatures of ferroalloys and steel is about 50°C, and the temperature between ice and water is 25°C, the obtained indicators for this parameter should be reduced by 2 times. In addition, the density ratio of liquid steel to water, which is 7000/997 ~ 7, must be considered. Thus, the real-time scale for modelling will be 3.5:1 (all processes in the model will occur approximately 3.5 times faster than in the real furnace).
To assess the speed of metal phase movement in the crucible of an induction furnace, the term stirring index (SI) is used [17], which can be calculated by the Eq. 1

$$SI = \frac{60{,}000 \cdot \sqrt{\dfrac{kW \cdot D}{SG \cdot \rho \cdot f}}}{A} \qquad (1)$$

kW is the power of the induction furnace, kW;
f – operating frequency, Hz;
D – diameter of the furnace crucible, m;
SG – specific density of liquid metal in the inductor, kg/m^3;
ρ – resistivity of metal in the furnace crucible, μΩ·cm;

A is the area of the cross-section perpendicular to the vertical axis of the crucible, m^2.

Thus, according to the calculations based on formula (1), it has been determined that the stirring index in the crucible of the laboratory furnace will correspond to flow velocities in the transparent low-temperature model of the crucible at a liquid flow rate that pumped through the pump at $5.83 \cdot 10^{-4}$ m^3/s.

In order to determine the optimal position for introducing alloying agents and ferroalloys into the crucible of the induction furnace, a series of tests was planned with variations in the introduction place both radially and in height within the crucible. The experimental conditions included introducing materials onto the surface of the melt near the crucible wall, at a distance of 1/4, 1/2, and 3/4 radius from the crucible wall, and directly on the vertical axis of the crucible. To determine the optimal height for introducing ferroalloys, experiments were conducted with the forced immersion of the test sample on the bottom of the crucible, at 1/4, 1/2, and 3/4 of the crucible height from the bottom, and on the surface of the melt. Studies on the influence of the depth of ferroalloy introduction were based on the most effective variant of radial introduction into the crucible. The dissolution process in the simulation model was accompanied by video recording, allowing for the determination of the hydrodynamic conditions of the process (predominant trajectories of ferroalloy lump movement in the melt volume under the influence of hydrodynamic flows), the time of model ferroalloy lump dissolution, and the time of homogenization of the melt model in the crucible.

Moreover, the influence of melt movement velocity in the induction furnace crucible on the efficiency of ferroalloy dissolution processes and melt homogenization in the crucible was investigated. This was based on the best introduction variant identified in the previous research stage. The research methods and monitored parameters were similar to those of the previous case.

Each experiment was repeated three times. In addition to visual observations of the ferroalloy fragment, the criteria for the complete dissolution of the fragment and the complete homogenization of the metal bath was the absence of a gradient in the intensity of the liquid color (determined based on the video recording).

RESULTS AND DISCUSSION

Determination of the rational place for introducing the ferroalloy/deoxidizer by the radius of the induction furnace crucible and its height. In the first stage, the efficiency of dissolving a fragment of ferroalloy in the melt in the middle of the crucible of an induction furnace was investigated. In particular, consider the behaviour of a piece of ice imitating a ferroalloy at different places of its introduction into the model. Figure 2 shows characteristic trajectories of the movement of the ice piece and its dissolution, for example, when introduced near the wall (A), at a distance of 1/2 the radius (B) and in the centre of the model (C). The images for a distance of 3/4 of the radius were similar to those for 1/2 of the radius and at 1/4 of the radius were similar to those obtained when introduced near the wall, so that they are not shown.

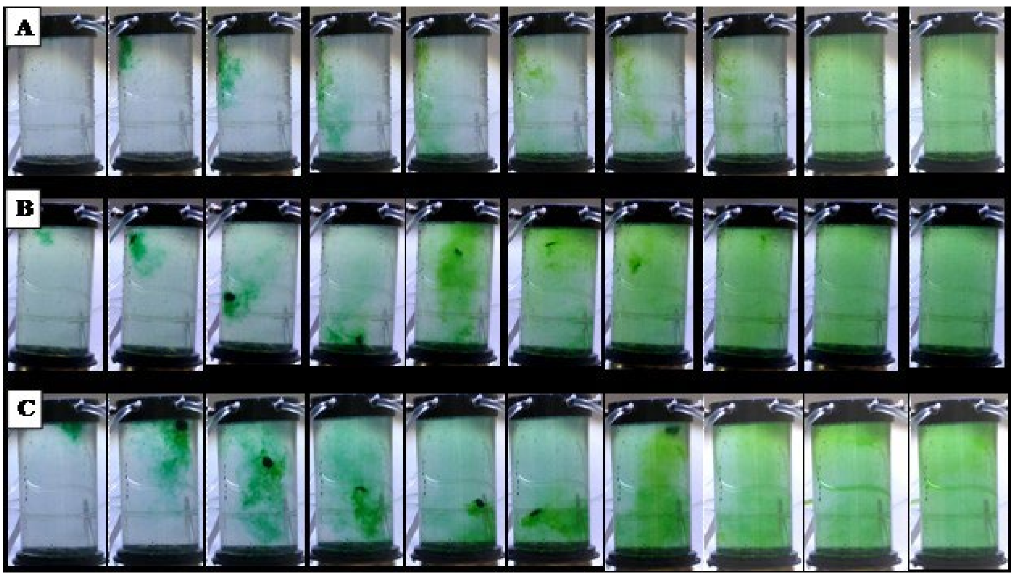

Fig.2 - Images of the trajectory of the ice piece simulating the ferroalloy and its gradual dissolution when placed: A – near the wall, B – at a distance of 1/2 of the model radius and C – at the center.

According to the data presented in Fig. 2, it can be concluded that the optimum radial position for introduction into the induction furnace crucible is a distance greater than 1/2 of the radius from the crucible wall. In cases where it is less than 1/4, the ferroalloy is "forced" to the wall by flows or holding it on the surface, which increases the time for the melt to absorb the ferroalloy and creates conditions for significant oxidation of its constituents by atmospheric oxygen. When ferroalloys are introduced into the specified area (more than 1/2 of the radius), they are captured by the liquid phase flows and introduced into the melt volume. This leads to rapid dissolution of the ferroalloy fragment in the melt volume, preventing oxidation of its constituents by atmospheric oxygen. Centre introduction reduces the dissolution rate of the ferroalloy fragment, possibly due to upward flows at the centre of the model, which slows down its capture by the volume.

To evaluate quantitatively the effectiveness of different radial positions for introducing ferroalloys into the induction furnace crucible, a dependence of the time of dissolution of the ferroalloy fragments and the time of homogenization of the liquid phase on the insertion distance from the wall was built using averaged data (Fig. 3).

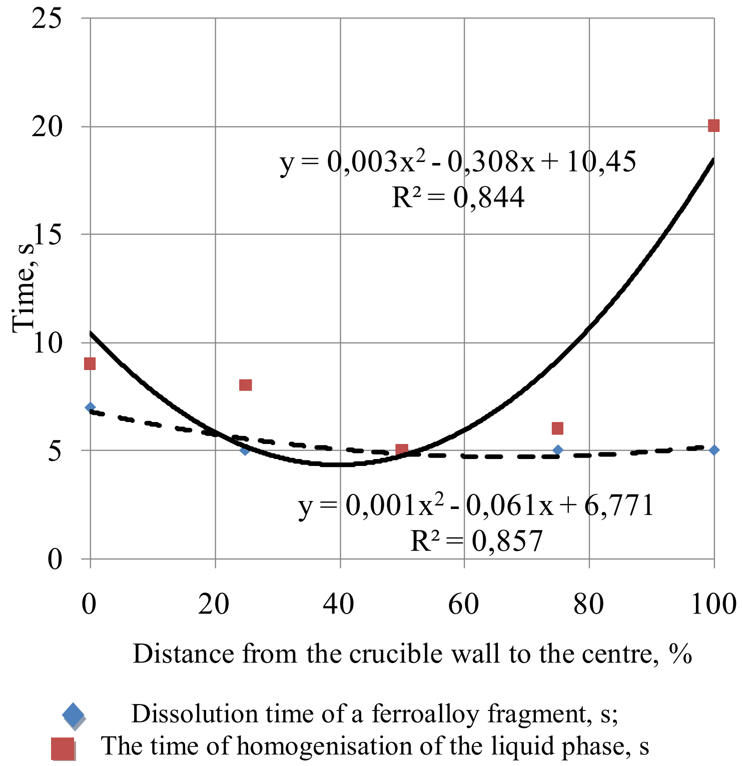

Fig.3 - Dependence of the dissolution time of the ferroalloy fragment and homogenization of the liquid phase on the place of ferroalloy introduction, obtained from the results of low-temperature modelling based on averaged experimental data.

From the data it can be concluded that there is an optimum radial place for introducing ferroalloys into the crucible, which is at a distance from the wall of 1/2 of the crucible radius. In this case, the processes of dissolution and redistribution in the liquid phase are coordinated by the organization of the hydrodynamic flows in such a way that they keep the ferroalloy fragment in the volume of the liquid phase. When the ferroalloy fragment is introduced closer to the crucible wall, melting occurs at the surface of the liquid phase, and redistribution in the melt volume is significantly difficult because of the presence of a stagnant zone.

The results of determining the hydrodynamic characteristics (dominant trajectories) of the interaction of the ferroalloy fragment with the liquid metal under different conditions of depth and radial distance of introduction into the crucible of the induction furnace are presented in Fig. 4.

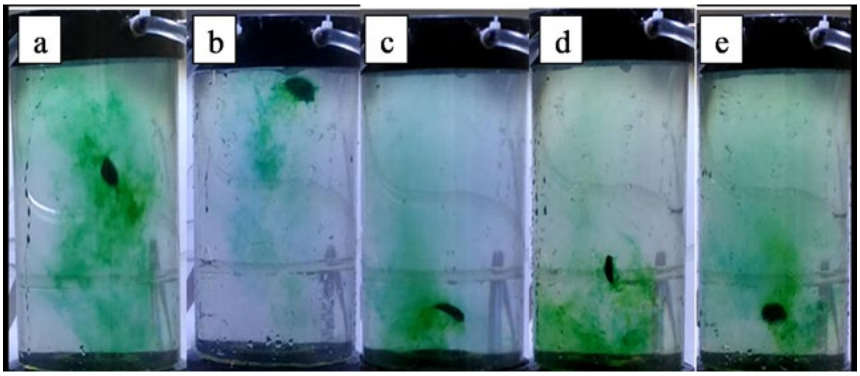

Fig.4 - Images of the interaction of the ferroalloy fragment with liquid metal for different introduction conditions along the height of the crucible of an induction furnace at a distance of 1/2 radius at the same time from the start of introduction – 1.5 s: a – introduction to the surface of the melt; b – introduction at 1/4 of the crucible height from the melt surface; c – introduction at 1/2 of the crucible height from the melt surface; d – introduction at 3/4 of the crucible height from the melt surface; e – introduction to the crucible bottom.

From the data presented in Figure 4, it can be concluded that in all cases, the dissolution of the ferroalloy fragment takes place in the melt volume, which positively affects its efficiency in being assimilated by the metallic phase. For a quantitative assessment of the trend identified, a graphical dependence of the time of dissolution of a ferroalloy fragment and homogenization of the liquid phase was built on the depth of introduction of a ferroalloy fragment into the melt (Fig. 5).
According to the data presented in Figure 5, there is a trend confirming the increase in the efficiency of the deoxidation and alloying processes with an increase in the depth of material introduction into the melt. This can be explained by more intensive stirring in the melt volume and, consequently, an increase in the efficiency of the element redistribution process throughout the melt volume. Based on the experimental studies carried out, this is confirmed by a significant decrease in the bath homogenization time with an increase in the depth of introduction, with a slight influence of the dissolution time of the ferroalloy fragment.

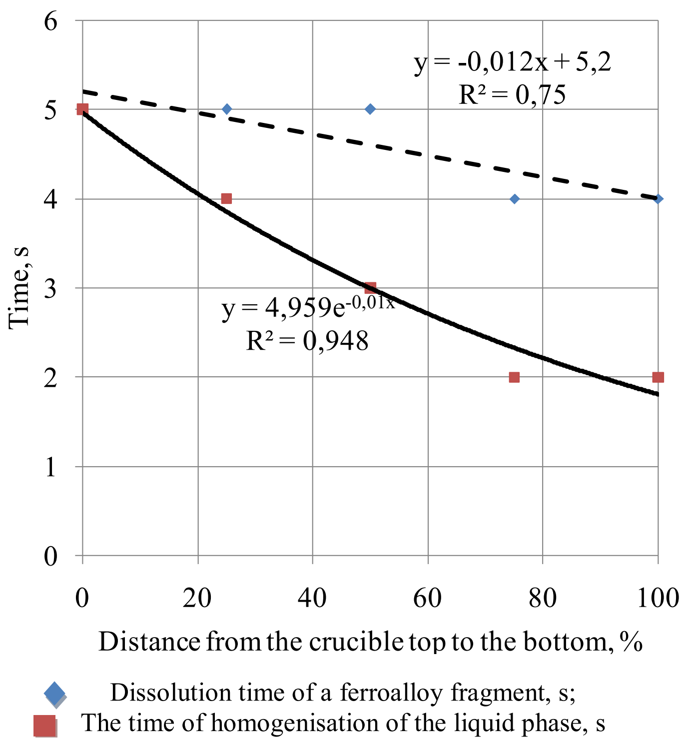

Fig.5 - Dependence of the dissolution time of ferroalloy fragments and liquid phase homogenization on the place of ferroalloy introduction as a function of model height, obtained from the results of low-temperature modelling based on averaged experimental data.

Determination of the influence of the melt stirring speed on the bath homogenization rate. The next research stage was to determine the influence of the melt stirring speed in the induction furnace crucible on the alloy and ferroalloy dissolution processes using identical ice fragments introduced at the same place in the model. The results of the quantitative assessment are illustrated in Figure 6. The data show that an increase of 40-50% in the stirring speed reduces the dissolution and homogenization time by almost 2 times. This effect is associated with increased efficiency of the mass exchange processes in the metal bath due to forced convection.

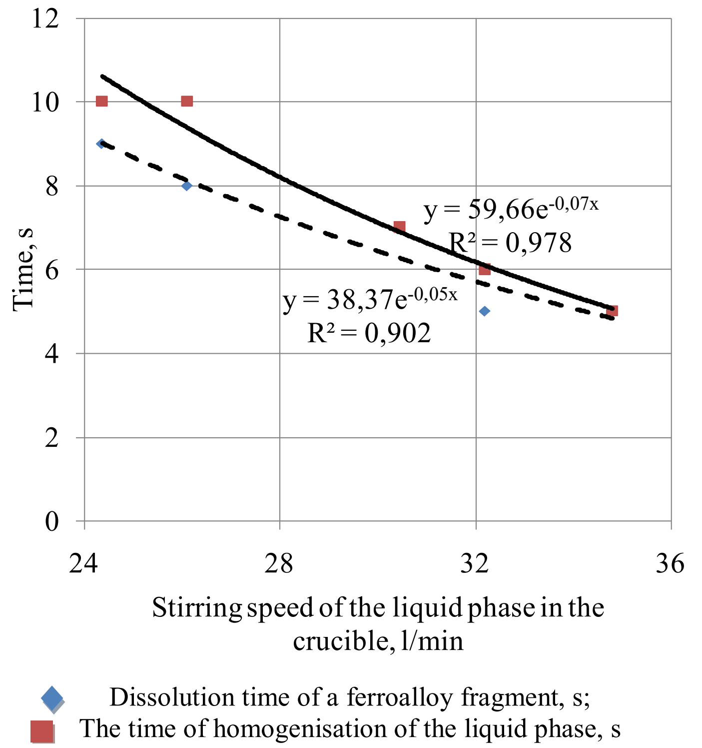

Fig.6 - Dependence of the dissolution time of ferroalloy fragments and liquid phase homogenization on the stirring speed of the liquid melt in the volume of the induction furnace crucible.

Summarizing the results on the low-temperature modelling of the processes of interaction of ferroalloys with the liquid bath of an induction furnace by the example of the interaction of colored ice and water, it should be noted that the most rational place for the introduction of ferroalloys into the crucible of an induction furnace is the area of the melt located at a distance of 1/2 radius from the centre of the crucible. In this case, due to the characteristics of the hydrodynamic flows that formed in the furnace crucible, there is an effect of keeping the ferroalloy fragment within the volume of the metal melt throughout the complete dissolution process.

Regarding the depth at which the ferroalloy is introduced into the melt volume, the observed tendency is the dissolution time to decrease when the depth of the ferroalloy as introduced into the melt increases. However, in the production conditions, it is very difficult to obtain the introduction of deoxidizers and alloying agents into the volume of the metal melt, so their introduction is carried out on the surface of the melt.

Thus, according to the results of the conducted low-temperature modelling, it was established that when introducing a hemispherical ferroalloy fragment with a diameter of 20 mm at a distance of 1/2 of the radius of the induction furnace crucible, the time of complete dissolution is 5 s that in terms of the actual process in the furnace will be 5·7/2 = 17.5 s. The data obtained correspond to the results of studies on the dissolution of ferromanganese fragments of different fractions in a metal melt [10], which indicates the consistency of the data obtained with production conditions. It should be noted that deoxidation processes are significantly influenced by the processes of oxygen redistribution and removal from the melt of the products of their interaction with deoxidizing and alloying elements

[18]. Based on this, the required holding time of the metal in the crucible of the laboratory induction furnace with a capacity of 10 kg is at least 5 minutes, and for production conditions (crucible capacity up to 150 kg), it is 10-15 minutes.

Considering the features of the affinity of alloying elements for oxygen (Fig. 7) and the essential for guaranteed removal of non-metallic inclusions formed in the melt, the following scheme of deoxidation and alloying is proposed.

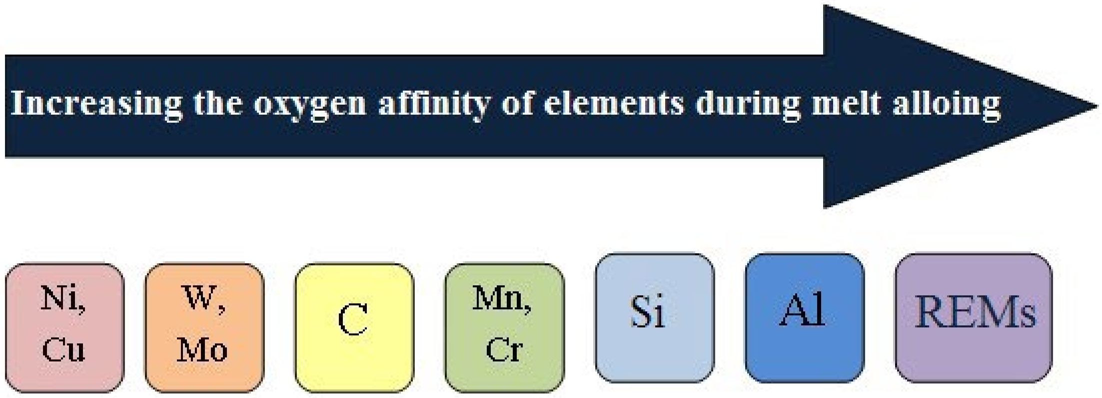

Fig.7 - Features of the affinity of alloying elements for oxygen [18].

The first stage is the introduction of aluminium or silicon into the melt for deep deoxidation. Afterward, the introduction of elements with low affinity for oxygen (nickel, copper, tungsten, and molybdenum). Further, at the next stage is manganese and chromium. Then is carbon (during deoxidation, gaseous products are formed, which additionally remove non-metallic inclusions from the melt). The last stage is the introduction of rare earth materials for the final modification of the structure of both the finished steel and non-metallic inclusions.

CONCLUSION

Based on the results obtained from the low-temperature modelling of the interactions between ferroalloys and the molten bath of an induction furnace, exemplified by the interaction of colored ice fragments with water, it should be concluded that the most rational place for the introduction of ferroalloys into the crucible of an induction furnace is the area of the molten bath located at a distance of 1/2 the radius from the centre of the crucible, with better results being obtained by avoiding the central area. At the same time, due to the features of hydrodynamic flows formed in the furnace crucible, the effect of holding a ferroalloy fragment in the volume of the metal melt during the time of complete dissolution is observed.

Concerning the depth of introduction of the ferroalloy into the volume of the crucible, there is a tendency for the dissolution time to decrease with increasing depth of introduction into the melt. However, in real production conditions, it is very difficult to obtain the introduction of deoxidizers and alloying agents into the volume of the molten metal; therefore, their addition is carried out on the surface of the melt. Consequently, there is a reason for holding the melt when introducing a ferroalloy.

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