Chapter 8
Basic Physical–Chemical Processes in Liquid Bath: Process Mechanisms

8.1 Interaction of Oxygen Jets with the Bath: General Concepts

Until oxygen has become readily available on industrial scale, the source of oxygen intake into the bath of EAF used to be the atmosphere of the freeboard and the additions to the bath which contained ferrous oxides. Presently, only ferrous oxides introduced into the bath with the oxidized scrap must be considered as an additional source of oxygen. The furnace atmosphere has practically lost its significance as a source of oxygen. This has happened as a result of elimination of significant air infiltration into the furnace during the operation with closed slag door as well as sharp shortening of tap-to-tap time.

In the modern furnaces, practically all oxygen used during the heat is introduced into the bath by the high-velocity oxygen jets. These jets, depending on the amount of stored energy at the moment of impact with the bath, penetrate the bath to a greater or smaller depth, Fig. 8.1a, b. The hydrodynamic processes taking place during the oxygen blowing are quite complex and will be reviewed in detail in the following chapters. Here it is sufficient to consider only their certain most important

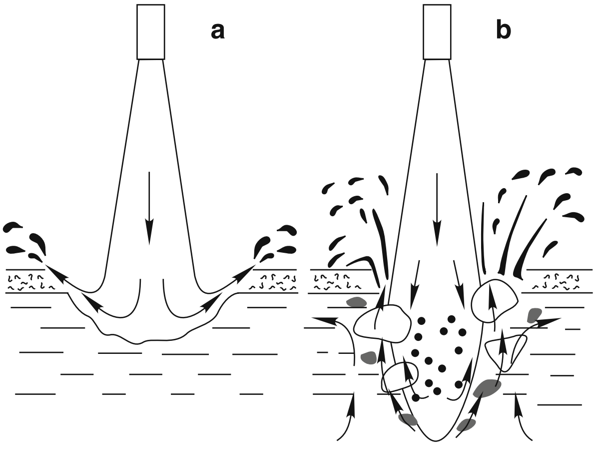

Fig. 8.1 Modes of interaction of the oxygen jet with the bath (elucidations are given in the text)

Y.N. Toulouevski, I.Y. Zinurov, *Innovation in Electric Arc Furnaces*,
DOI 10.1007/978-3-642-03802-0_8, © Springer-Verlag Berlin Heidelberg 2010

features and point out that hydrodynamics of oxygen blowing greatly affects the physical–chemical processes in the bath, which, in turn, determine the final results of the heat. These processes include mainly oxidation of carbon as well as that of iron and its alloys, heating of the liquid metal by the external and internal energy sources, and melting scrap in the liquid metal.

When jet power is relatively low, the crater is formed on the surface of the bath. The reverse flow of oxygen blows splashes of metal and slag out of the crater, Fig. 8.1a. As the jet power rises the jet penetrates through the layer of slag and partially enters into the metal forming the so-called reaction zone. This case is mostly typical in practice. In the special literature, the space of jet immersion into the melt is divided sometimes into two reaction zones – primary and secondary. For the purposes of this book such detailing is deemed not necessary. Therefore, in the text below we consider the reaction zone as the entire, though quite limited in dimensions, space of jet immersion into the melt as opposed to the rest of the bath where the chemical transformations of the elements take place as well.

In the reaction zone, the metal and the slag are drawn into the oxygen jet, and both the jet and the melt are being atomized into separate gas volumes and droplets. When oxygen is in excess, some volumes of gas rise to the surface of the bath and increase splashing. Droplets of metal are oxidized in oxygen and are converted into ferrous oxides. These oxides are partially consumed for oxidizing other elements, carbon in particular, right in the reaction zone. They are partially dissolved in the metal, thus increasing oxygen content in it. A small fraction of the oxides rises forming the slag. The rest of ferrous oxides are spread all over the bath. This process is promoted by the intense turbulent pulsations in the reaction zone, which are transferred to the rest of the metal.

Spread of oxygen throughout the volume of the bath is also promoted by the high temperature of the reaction zone, which varies from 2200 to 2600°C depending on the periods of the heat. Solubility of oxygen in liquid iron increases sharply as temperature rises. In the reaction zone oxygen solubility is equal to 1.5–2.5%, and beyond its boundaries at the temperature about 1600°C its value is only 0.2%. Therefore, when the metal moves from the reaction zone to the bath areas with relatively low temperatures, oxygen evolves from the solution as finest particles of FeO with well-developed surface, which promotes the oxidation processes.

When oxygen is blown from below or from the side, the structure of the reaction zone is approximately the same as when oxygen is blown from above. However, when blowing from below is used, gravitation forces do not obstruct the spread of the oxygen jet as with blowing from above, but promote it. Therefore, the length of the reaction zone increases.

8.2 Oxidation of Carbon

According to the modern concepts, oxidation of carbon as well as of a number of other elements in the steel melting bath is a complex multistage process. Certain details of this process have been a subject of scientific discussions for a long time.

Without going deep into details posing rather academic than practical interest, let us concentrate on the basic concepts, which have to be considered when resolving problems regarding intensification of decarburization processes.

As has already been mentioned above, in good accord with the laws of physical chemistry and industrial data, it is generally assumed that under conditions of steel melting bath carbon is oxidized only to CO. It is known that negligible portion of carbon can be oxidized to CO_2 as well, but from the practical point of view this process can be ignored.

The rate of chemical reactions increases greatly, as the temperature rises. At the temperatures of steel bath equal to 1480–1650°C the rate of carbon oxidation by oxygen reaches the values so high, that this rate itself does not restrict in any way the possibilities of intensification of decarburization process. However, in order to enable this reaction, carbon and oxygen must come into direct contact. For sustaining the process of decarburization, it is necessary to continuously deliver carbon and oxygen into the reaction zone and remove the product of reaction CO from there.

Rising to the surface and removal of gas bubbles of CO from the bath occurs quite intensely and does not hinder the process. Observations show that evolution of CO occurs quite uniformly across the entire surface of the bath without obvious dominance of reaction zones. Therefore, the area of oxidation of carbon is the entire bath where carbon is spread relatively uniformly. On the contrary, the sources of incoming oxygen are concentrated in quite limited in volume reaction zones. Such a depiction of the process is well in accordance with the simplified working model of the bath decarburization process, i.e., with so-called two-stage scheme of oxidation of carbon.

According to this scheme, the primary chemical act of blowing the bath with oxygen is oxidation of iron. This assumption is quite obvious since almost 100% of the bath consists of iron, and this element is the first to be oxidized. Then, the ferrous oxides formed in the reaction zones spread throughout the bath. They act as a transmitter of oxygen, which is consumed for oxidation of carbon and other elements, alloys of iron. This scheme agrees well with the depicted above scheme of interaction of oxygen jets with the bath. As applied to the EAFs and other hearth furnaces, this scheme is accepted by most metallurgists.

It is necessary to stress that the two-stage scheme does not exclude the possibility of direct oxidation of carbon in the reaction zones, but this process is given a secondary role. It should be mentioned as well that in oxygen converters, where relative intensity of oxygen blowing (m^3/ton min) is a few times higher than in the hearth furnaces, up to 70–80% of all the carbon can be oxidized in a reaction zone, according to some specialists.

Two-stage scheme explains quite obviously why the transfer of ferrous oxides from the reaction zones to the other areas of the bath is the stage of the decarburization process, which limits the rate of the whole process. If this transfer was just due to the gradient of concentrations and temperatures in the different areas of the bath, i.e., due to the quite slow process of molecular diffusion, the modern rates of heat in the EAFs would not be even remotely achievable. In reality, the bath is stirred intensely by the turbulent metal flows, which result mostly from the dynamic effects of the oxygen jets and CO bubbles on the bath. Under these conditions, the rate of oxygen transfer increases by many times.

Issues of the bath stirring will be reviewed in the following chapter. It should be added here that the role of the bath stirring increases even more when low-carbon steels are produced. When at the end of the heat carbon content drops below 0.2%, the rate of the further bath decarburization is limited to even greater extent by transfer of not only oxygen but carbon as well.

8.3 Melting of Scrap

The features of melting scrap in iron–carbon melt have been studied under laboratory conditions by melting samples in small induction furnaces as well as under industrial conditions in steelmaking units using the method of radioactive isotopes. The isotopes used were those which are practically not possible to oxidize in the steel melting bath, e.g., cobalt isotope. This isotope and other isotopes were introduced into liquid bath at the beginning of scrap melting; and then the radioactivity of metal samples was being measured during the heat. As mass of the liquid bath increased due to melting of scrap, the concentration of isotope in metal and the radioactivity of the samples decreased. This allowed estimating the intensity of the melting process.

Melting of scrap in a liquid bath is significantly different from melting by electric arcs in a freeboard. Rate of melting by the arcs is determined only by the processes of heat transfer from the arc plasma to the surface of scrap lumps. Melting in the liquid bath is complicated by the involvement of mass transfer processes. It has been determined that depending on the melt temperature and carbon concentration, as well as on the temperature of scrap preheating, it is possible to divide the overall duration of scrap melting at the liquid bath into three typical stages.

First stage: freezing of the melt. As cold or slightly heated scrap is immersed into the bath, there is a short period when the melt freezes over the surface of the lumps forming a solid crust. At the beginning, the thickness of this crust grows rapidly. Then, as the heating progresses and scrap temperature increases, this growth slows down due to reduced heat flux from the crust inside the lump. At the moment when this heat flux and heat flux from the melt toward the surface of the crust become equal, the growth of the crust stops and the crust thickness reaches its maximum. As the scrap temperature continues to rise, the crust starts to melt and then disappears.[1] The smaller the mass of scrap lump and the initial temperature differential between the scrap and the melt, the smaller the thickness of the crust and the time it exists.

Second stage: diffusion melting. This process takes place during scrap melting in iron–carbon melt, for example in hot metal, when the temperature of the melt is significantly lower than the scrap melting temperature (1530–1540°C). In case of hot metal this difference is 200°C. The diffusion melting of scrap plays a significant role during the initial stage of heat in a converter. It can take place in the EAFs as well, especially in those which use hot metal in large amounts. Melting of scrap in hot metal would be impossible without diffusion of carbon from the melt into the surface layer of scrap lumps. As this layer is enriched with carbon, its melting temperature becomes lower than the temperature of the melt. The scrap, layer by layer, is converted to a liquid state and mixes with the bath.

The term “melting” itself does not correspond fully to the nature of the described process intimately associated with diffusion of carbon. On the other hand, the term “dissolution,” which is also widely used for this process depiction, is not quite applicable since dissolution means mixing with the bath through diffusion without preliminary transition of iron into a liquid state. While further using the term “diffusion melting of scrap” it should be assumed the entire complex of thermal and diffusion processes.

Third stage: intensive melting. Such melting starts as soon as the melt temperature is significantly higher than the scrap melting temperature. Intense supply of heat to the surface of the scrap lumps resulted from the temperature difference and turbulent stirring of the bath assures greatly high rate of melting during this stage. It is worth noting that intensive stirring is a necessary condition required to reach such rates.

Powerful electric arcs and release of large amounts of chemical heat due to intensive oxygen use in modern furnaces assure a rapid growth of bath temperature. Calculations and special research data show that under these conditions, contrary to the heat in a converter, the stage of melt freezing is not quite explicit. This difference can be explained also by the fact that the EAFs use light scrap, while the converters use heavier scrap. Freezing of the melt over light scrap can take place, but it is very short-lived and happens only over some larger lumps. Therefore, it does not affect significantly the duration of scrap melting and electrical energy consumption.

The same can be said regarding the second stage – diffusion scrap melting. Diffusion of carbon from the melt to the surface layer of solid scrap is quite slow process compared to the rate of the bath temperature rising. Besides, unlike in converters, the carbon content in the EAF bath is not quite different from that of the scrap. The exceptions are the furnaces which use hot metal or reduced iron (DRI, HBI), where the carbon content could be 1–2%. In those furnaces, the conditions corresponding to the second stage can occur for quite brief periods of time.

Thus, in order to achieve high productivity, the scrap immersed into the liquid bath must be melted under the conditions of the third stage, i.e., when the melt temperatures greatly exceed the scrap melting temperature. Then, for a short tap-to-tap time, very fast heating of the liquid bath is required.

It is known, Chap. 1, Sect. 1.3.3, that at the present time most of furnaces operate with so-called “hot heel.” Such a technology requires that the slag and approximately 15–20% of the metal from the previous heat are left on the furnace bottom. Presence of the hot heel significantly affects the process of melting of the scrap.

This effect is explained by the following. The light scrap, sheet bushelling for example, is placed in the bottom part of the charging baskets in order to avoid the damage of the bottom lining. As the first basket is charged, this scrap, which has a very large surface area, is immersed in the hot heel causing the temperature of the latter to drop by 100–200°C. Such an abrupt cooling of the hot heel with the low carbon content could slow down the heat process. But this is avoided by blowing oxygen into the melt. Blowing speeds up the melting of scrap by intensifying the melt stirring by O_2 jets and CO bubbles, amount of the latter is increased due to intensified oxidation of carbon. The early start of oxygen blowing is required when operating with the hot heel.

8.4 Heating of the Bath

Conditions of heat exchange determining the heating of the bath of the furnace are very complex. Heat from the external sources is delivered to the bath through its surface covered with slag as well as emitted inside the bath itself by internal energy sources. The external sources are electric arcs, oxy-fuel burners, and filling the furnace freeboard gases in case their temperature is significantly higher than the melt temperature. Such conditions are created by post-combustion of CO near the bath surface. The internal sources are chemical reactions of oxidation of carbon as well as iron and its alloys like Si, Mn, etc.

The bath loses heat through emission of CO bubbles, due to thermal conductivity through the lining of the bottom and the banks as well as due to radiation from the slag surface onto the water-cooled panels of the sidewalls and the roof. Great amount of heat obtained by the bath is consumed in heating and melting the scrap immersed in a bath. The main thermal losses of the bath are the losses through radiation and through emission of CO bubbles. The other losses can be ignored.

The main source of heat for the liquid bath is electric arcs, which heat it from above. During the last 30–40 years, electrical power of EAFs has more than quadrupled. On the 120-ton furnaces of a new generation, electrical power in the period of melting of scrap in the liquid bath reaches 120 MW. This power, at the efficiency coefficient of energy $\eta_{EL} = 0.70$, produces average specific heat flux of about $3000\,\mathrm{kW/m^2}$ per entire surface of the bath 6.2 m in diameter. This is more than 10 times higher than the specific heat flux of the oxy-fuel flames in the most powerful open-hearth furnaces operated with intensive use of oxygen.

It is necessary to take into account that heat flux from the arcs is unevenly distributed over the surface of the bath. Only a small area in the middle of the bath surface is directly heated by the arcs. Therefore, the real densities of the heat fluxes incident onto the bath from the arcs are much higher than the average value shown above. For the three-electrode furnaces the local flux densities are several times higher than the average ones, and those of the single-electrode DC furnaces are ten times higher. Let us ask the following question: what is the mechanism of absorption by the bath of enormous amounts of external heat supplied to the bath in a way which does not promote absorption?

It is known that a rational way of heating liquid is heating from below, Chap. 2, Sect. 2.4. During heating, the liquid is stirred intensely, which shortens the duration of heating and reduces energy consumption by many times. The stirring occurs due to the difference in density of the heated and relatively cold volumes of liquid. The heated, less dense liquid due to gravitational forces rises up, while the cold, denser liquid drops down. This type of stirring is called gravitational. It occurs by itself and does not require consumption of external energy. Gravitational stirring is highly intense, and its intensity increases proportionally to the increase in the power of heat energy source. As a result, during the heating from below, the temperature field in the volume of liquid remains rather uniform regardless of increasing power of the heat source.

The bath in EAF is heated from above. Such a type of heating does not produce gravitational stirring. In comparison to non-metallic liquids, liquid steel has high thermal conductivity $\lambda = 23\,\text{W/m} \times {}^\circ\text{C}$, Chap. 3, Sect. 3.2.2. Despite this, removal of heat from the arc zone only due to thermal conductivity of the bath would lead to absolutely unacceptable overheating of the upper layer of the bath. The fact that such a problem does not occur can be explained by intense stirring of the bath. Without intense stirring of the bath, the operation of the high-power EAF would be impossible.

The bath is stirred by the oxygen jets and the CO bubble rising to the surface. Electric arcs contribute to the stirring by exerting dynamic pressure on the bath surface. Lately, blowing the bath with inert gas is being widely used to further intensify the stirring. For this purpose, the special tuyeres are installed in the bottom of the furnace. For the high-capacity furnaces, the bottom blowing becomes mandatory.