Introduction:

A variety of lime products and blended lime products are used in the production of steel. In the electric arc furnace practice it is common to see high calcium pebble lime, dolomitic pebble lime and iron coated dolomitic pebble lime being charged over the roof in a bucket or through some type of feed system. New technologies are being developed to provide “co-jet” type injection of lime directly into the slag/metal interface for optimization of foamy slag characteristics.
Lime is critical to steelmaking. The science of how lime products interact with the various components formed during melting and during ladle refining has become the basis for understanding the old phrase “Make the slag and the steel will make itself.”

Steel production involves an *oxidation process* usually in the furnace and a *reduction process* usually in the ladle that depends on lime to refine impurities from the liquid metal through formation of a liquid slag that reacts with the liquid metal.

Remember, *oxidation* is simply the addition of oxygen into the furnace causing metals and non-metals to form oxides that are lighter than the liquid steel that float to the surface of the bath. Some metallic oxides are acid products which can react with the basic refractories of the furnace or ladle unless we make a basic slag using lime and dolomitic lime that will perform this function instead. The oxygen can also react with carbon to create a gas that provides bubbles for foaming the liquid slag and for chemical energy used in melting. Examples of different methods of getting oxygen into the metal and slag are shown below:
Steel Plant Training Course

Section II: What is Slag? Basic Steelmaking for Electric Arc Furnaces

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Badische Stahlwerks – Kehl, Germany
Oxygen blowing through slag door with pipe style manipulator – Oxidation Process

Gallatin Steel – Ghent, Kentucky
Oxygen blowing through slag door using supersonic lance – Oxidation Process
When you are blowing oxygen into the scrap metal and other metallics that have been charged into the furnace, the oxygen reacts with a portion of the metals to form a new compound with oxygen called oxides. These new compounds usually are acid compounds that react with the basic bricks in the furnace or ladles.

An example of the oxidation equations can be shown for oxidation:

- Aluminum: \(2(Al) + 3(O)\) reacts to give aluminum oxide \(\text{(Al}_2\text{O}_3\text{)}\) (acid oxide)
- Silicon: \((Si) + 2(O)\) reacts to give silica \((\text{SiO}_2\text{)}\) (acid oxide)
- Iron: \((Fe) + O\) reacts to give iron oxide \((\text{FeO}\text{)}\)
- Carbon: \((C) + O\) reacts to give \(\text{CO} + (O)\) reacts \(\text{CO}_2\) (bubbles) (energy)

It can be seen that there are differences in some of the properties of metals and then when they combine with oxygen to form new compounds called “oxides”. Metals and their oxides have tremendous differences as can be seen in the Table I below:

<table>
<thead>
<tr>
<th>Metal</th>
<th>Symbol</th>
<th>Oxide</th>
<th>Oxide Name</th>
<th>Oxide Color</th>
<th>Metal Melting Temperature</th>
<th>Oxide Melting Temperature</th>
<th>Found in or as</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron</td>
<td>Fe</td>
<td>FeO</td>
<td>Wustite</td>
<td>Black</td>
<td>2799 °F</td>
<td>2840 °F</td>
<td>rust, iron ore</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fe2O3</td>
<td>Hematite</td>
<td>Red</td>
<td>2800 °F</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fe3O4</td>
<td>Magnetite</td>
<td>Black</td>
<td>2800 °F</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminum</td>
<td>Al</td>
<td>Al2O3</td>
<td>Alumina</td>
<td>White</td>
<td>1220 °F</td>
<td>3,630 °F</td>
<td>bauxite, bricks</td>
</tr>
<tr>
<td>Silicon</td>
<td>Si</td>
<td>SiO2</td>
<td>Silica</td>
<td>White</td>
<td>2570 °F</td>
<td>3137 °F</td>
<td>sand, ash in coal, dirt</td>
</tr>
<tr>
<td>Magnesium</td>
<td>Mg</td>
<td>MgO</td>
<td>Magnesia</td>
<td>White</td>
<td>1202 °F</td>
<td>5072 °F</td>
<td>material, bricks</td>
</tr>
<tr>
<td>Calcium</td>
<td>Ca</td>
<td>CaO</td>
<td>Lime</td>
<td>White</td>
<td>1580 °F</td>
<td>4,658 °F</td>
<td>lime, cement</td>
</tr>
</tbody>
</table>

Table I. Shows the differences in melting points and colors of the oxides seen in slags.
**What is slag?** Slag can look differently depending when you are looking at it and the chemistry of the slag is what influences how it looks during molten conditions. In the furnace during melting, the slag can be creamy and fluffy, it can be very fluid and watery or it can be very thick. There are reasons why the slag looks this way and what we want to understand is what causes this so we can achieve the creamy slag that will foam to protect the furnace.

If you take a slag sample from the furnace and let it cool it will look very black, that is because of the “dark oxides” like iron oxide and manganese oxide that make it appear black. These were produced during the “oxidation phase” of melting.

**Slag comes from 4 primary sources:**

- Oxidation of metallic elements in the base metal
  - Aluminum, silicon, chromium, manganese, titanium, etc.
- Non-metals
  - Sulfur and phosphorus
- Flux Additions
  - Dolomitic lime, high calcium lime, spar, calcium aluminates
- Dissolved Refractories
  - CaO-MgO, Al₂O₃

It is important to know which oxides are acid and which are basic in order to know what kind of refractory bricks react with these oxides. An acid slag will erode furnace linings because the bricks are basic. An acid slag contains high amounts of SiO₂, Al₂O₃ which can make the slag thinner.

A basic slag contains oxides like MgO and CaO, which makes the slag thicker. FeO is the most important part of the slag in that it will cause lime to dissolve at lower temperatures by what we call “fluxing”. If you look at the melting temperature of CaO at 4,658 °F and MgO at 5,072 °F it can be seen why it would be difficult without FeO lowering the melting point to get lime or magnesia into solution where steel temperatures are below 3,000 °F. (*Table I*)

**What useful properties does slag have in electric furnace steelmaking?**

- It insulates the bath, reduces temperature losses
- It helps in de-phosphorization and absorbs some sulfur.
- It helps control the types of inclusions and traps them in the ladle.
- It controls the steel oxygen levels and chemistry of the steel.
- Can protect steel from oxygen and nitrogen pickup.
- It protects the furnace from arc flare and refractory erosion.
Furnace Slags:

Some oxides introduced during the melting of scrap gives us no energy. They require more fluxes, which reduces iron yield. A consideration has to be made for SiO₂ contents in injection carbon, dirty scrap or silica in other materials charged in the furnace.

On the other hand, metals that do oxidize and hurt yield also help provide chemical energy. There has to be a balance considering the cost advantages between these concepts of energy and material requirements. Cheap scrap may not make steelmaking cheap!

The main functions of furnace slag is removal of phosphorous, coating of the furnace to protect refractories and shell, shield the arc and increase electrical efficiency.

There are four principles in controlling slags in steelmaking:

- **Minimum slag formation** – EAF
  - Minimum covering of the metal bath is required
  - Minimum B₄ basicity – basic oxides/acidic oxide ratios
- **MgO saturated slags** – EAF & BOP
  - Zero refractory gunning and increase in productivity
  - B₄ basicity of 1.8 to 2.3 (CaO + MgO/SiO₂ + Al₂O₃)
- **Foamy Slag Control** – EAF
  - Foam at right time and long enough – viscosity
  - Fluffy to creamy slag (saturated with CaO + MgO)
  - Control of FeO, C injection and control of oxygen blow
- **Balance of steel and slag in the steelmaking process** – “equilibrium”

**Phosphorous removal:**

There are two points to consider in using oxygen for making steel, it is important for phosphorous removal and carbon removal (decarburization).

The balance of oxygen activity in the steel and slag can be related in the oxidation phase as well as materials being used for dephosphorization. The equation of removing phosphorous from the steel is in simple terms is like an old fashion balance. In looking at the equation for this process:

\[
\begin{align*}
2P + \text{CaO} + 5\text{FeO} & \rightarrow \text{P}_2\text{O}_5 \cdot \text{CaO} + 5\text{Fe} \\
\text{(oxygen activity)} & \rightarrow 2990 \text{ F}
\end{align*}
\]
All this shows is that to remove phosphorous from the steel you have to add the things that react on the left side which is lime (CaO) and oxygen (FeO) to produce the product of $P_2O_5 \cdot CaO$ on the right side of the equation to trap in the slag. However, if you let the temperature go over 2990 °F before allowing the slag to come off you will reverse the reaction and you will get re-phosphorization! If you want to remove more phosphorous, add more lime, blow the heat down more (oxygen activity) or keep it cooler.

Many reactions in steelmaking can be considered as a balance as we mentioned above. In order to control the oxygen levels in the furnace or the ladle you have to consider this balance concept.

The following example of a simple balance shows that there is a relationship between the slag and the liquid metal either in the electric arc furnace or in the ladle. Before the oxygen reactions can take place in the liquid steel, the slag has to have the oxygen increase through formation of FeO, which provides for oxygen activity in the slag and steel. If the oxygen activity is high in the slag, then the oxygen activity in the steel will increase. In the case of steel in the ladle, if the oxygen activity is low in the slag, then the oxygen activity in the steel will decrease. This balance is called *equilibrium*. 

![Slag - Metal Chemical Balance](image)

*Fig. 1 Diagram showing balance concept between slag and metal*
Coating of the furnace for refractory and shell protection:
Slag is important to protect the furnace. It has to be the right kind of slag in order to do this. The chemistry of the furnace refractories is “basic” which means that acid oxides as well as FeO will attack and erode them by chemical action. The slag must be balanced toward the basic side to prevent slag erosion and for promoting foaming action. This is why we add CaO (high calcium lime) and MgO (dolomitic lime) to the slag.

Coating the furnace shell can reduce the heat loss during the cooling of the shell and save energy costs. Let’s take a look at the slag chemistry and what it means for slag foaming and refractory protection.

Slag Basicity:
The term slag basicity is a means in which steelmakers refer to how acid or how basic a slag is in relationship to the basic refractory utilized in furnace and ladle vessels. If the slag is more acid it will erode the bricks, if it is more basic it will protect the bricks.

The basicity of the slag is normally fixed by the amount of lime and dolomitic lime added, the silicon and aluminum levels of the metals charged as well as alloys. As you go lower in the ratio towards 1:1, we tend to think of that as being acid and the higher the ratio towards 2:1 we tend to think of that as being basic.

The following is an example of different slag ratios that are commonly used in steelmaking:

- B3 ratio = CaO% / SiO2% + Al2O3% + TiO2% - EAF
- B4 ratio = CaO% + MgO / SiO2% + Al2O3% + TiO2% - Normally - EAF
- B5 ratio = CaO% + MgO% / SiO2% + Al2O3% + CaF2% + (FeO% + MnO%)  
  If the FeO + MnO components are less than 5% they can be used in this equation. Although typically they are not introduced at all.

Therefore if we have lime (CaO) at 30% in the slag and the SiO2 is 18% with Al2O3 at 8%, we would have a B3 ratio of 1.15, which is more acid in the way it acts on refractories. If we have lime at 45% in the slag and the SiO2 is 15% with Al2O3 at 6% we would have a B3 ratio of 2.14, which is more basic in the way it acts on refractories. What are the relationships of MgO and CaO and how do they make the slag foam and protect the furnace at the same time? Let’s review the main parts to this process involving MgO, FeO, oxygen content of the steel, temperature and lime additions.
Why is MgO important to basicity? The slag contains dissolved calcium compounds and acidic compounds that cause MgO to dissolve from refractory brick into the slag. MgO will dissolve into the slag based on relationships of FeO content, basicity and temperature. The lower the slag basicity, the higher the MgO requirement for slag. An increase in FeO and temperature also increases the MgO requirement of the slag. The effects on MgO can be seen in the diagram below:

![Graphical representation of the main effect (in wt% MgO) of factors](image)

From the Figure 2, basicity is the most significant factor on magnesia saturation. Increasing FeO and temperature also have an effect in magnesia dissolution. The percent of MgO versus the basicity of a slag for dual saturation with CaO is shown in Figure 3 below:

![% MgO vs. Basicity for Dual Saturation](image)

**Fig. 2** Graphical representation of the main effect (in wt% MgO) of factors

**Fig. 3** Relationship of basicity and MgO dissolution for dual saturation in a slag.

An example of this relationship for the MgO % that can go into a slag to achieve dual saturation of dicalcium silicate $\text{Ca}_2\text{SiO}_4$ - (C2S) and Magnesio-Wustite ($\text{FeO} \cdot \text{MgO}$) - (MW) is given that for a basicity of 1.5 the %MgO required by the slag would be 12.5% and for a basicity of 2.0 the % MgO required by the slag would be about 9 %. Therefore refractory wear would not be seen in any case if the MgO is added by additions of dolomitic lime early in the steelmaking process to satisfy these requirements.

**Slag Foaming:**

Several factors must be met in order to produce a slag that will foam:

- Slag must contain FeO – must be enough to react with carbon to make CO bubbles
- Correct *viscosity* or consistency to hold the bubbles as long as possible.
- Sufficient MgO to minimize refractory wear and promote foaming

In trying to make the right slag for foaming it is sometimes good to think about comparisons of *viscosity* that allows the bubbles to stay longer in the liquid. If you blow air into chocolate milk, you get it to foam up and hold bubbles. If you tried it in water, it is too thin and bubbles would disappear quickly. If you tried it in a thick malt, it would not form bubbles for foaming. So, the slag can’t be too thin or too thick in order to hold the bubbles and make it foam for the time it is needed in the furnace.

The equation that can express how bubbles are made in the slag can be seen below:

$$
\text{C (Carbon)} + \text{FeO (Slag)} \rightarrow \text{CO \uparrow \ (bubbles)} + \text{Fe \downarrow \ (steel)}
$$

An addition of carbon to the slag prevents a yield loss because (FeO) is put back into iron in the bath and creates a CO bubble to foam the slag! Furnace slag viscosity is determined by the ratio of slag components and how those components make the slag thin or thick. It is the balance of these components to make the correct slag viscosity to hold the bubbles longer. The table below shows these components in the slag and what they do to the slag viscosity:
Table II. Slag Components and Influence on Viscosity

<table>
<thead>
<tr>
<th>Slag Component</th>
<th>Action on Slag</th>
<th>What determines its % in the slag?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al2O3</td>
<td>Thinner</td>
<td>Scrap Mix</td>
</tr>
<tr>
<td>SiO2</td>
<td>Thinner</td>
<td>Scrap Mix</td>
</tr>
<tr>
<td>FeO</td>
<td>Thinner</td>
<td>Final C % in Steel</td>
</tr>
<tr>
<td>CaO</td>
<td>Thicker</td>
<td>High Calcium &amp; Dolomitic lime</td>
</tr>
<tr>
<td>MgO</td>
<td>Thicker</td>
<td>Dolomitic Lime</td>
</tr>
</tbody>
</table>

How do we determine how much of the fluxes do we need? In a process of looking at the balance concept, we can know how much of one item we are adding on one side and how much we will get on the other side of the equation. “Mass Balance” in simple terms is how much you put into the furnace system is equal to how much you get out of the furnace system. Pounds of material in must equal the pounds of material you get out! Let’s start by looking at our furnace practice.

**What will the final FeO % be in the slag?**

FeO in the slag is proportional to oxygen dissolved in the steel. In all slag /metal reactions there is a ratio between how much of one thing is in the steel and how much it is in the slag. This is called the Partition Ratio. Also, remember the balance concept that what you do to the slag you also do to the liquid steel because of what we call equilibrium, meaning that the steel and the slag want to come to a balanced condition.

There is also a relationship of carbon content in the steel controlling the oxygen content of the steel. When you get to low carbon levels, the oxygen will then react with iron to form FeO, which makes your slag thinner, and impacts yield losses. It can be seen from this chart that carbon influences the oxygen level in the steel.
Fig. 4 Relationship of carbon content with dissolved oxygen content in the steel

If you have a 0.023% carbon at tap you would expect the oxygen level to be around 750 ppm. Now, to determine the FeO content of the slag when you have 750 ppm at tap, you could expect the FeO content of the slag to be around 33% based on Figure 5.

The following chart shows the relationship of dissolved oxygen vs FeO in the slag:
Impact of silicon on use of lime and FeO contents in the slag.

One must consider that the SiO₂ content of the slag determines how much lime we use. It also lowers the yield. All material going into the furnace under oxidizing conditions will influence what requirements the slag will need and the cost of these additions as well as yield losses. The scrap mix influences the SiO₂ content of the slag because of use of pig iron, the type of scrap that is utilized and dirt in the scrap. Every pound of silicon reacting with oxygen will create 2.17 pounds of SiO₂. This will cause 5 pounds of iron to be lost to the slag as FeO. The reason is that there is an increase in slag volume by increasing the amount of acid material that has to be balanced by a basic material like lime. To calculate yield loss, convert FeO to iron you must multiply FeO % by 0.78. FeO is an important factor!
The following diagrams describe how this happens:

1 lb Silicon in scrap + Oxygen = 2 lbs of SiO₂ to the slag

2 lbs of SiO₂ in the slag x Basicity Ratio = Lime Requirement (lbs)

Lime lbs / CaO % = Total Slag lbs Created in Furnace

Total Slag lbs Created in Furnace x FeO % = Lbs of FeO lost to slag

Lbs of FeO lost to slag x 78% = Lbs of iron lost (yield)
Since FeO in the slag is one of the influences for MgO requirements you would need to understand how much MgO to use in your fluxes. We now refer to Figure 6 that shows the relationship of how much MgO is required for the FeO content of the slag. Also Figure 2 has to be taken in account because of the relationship of MgO required for slag basicity.

**Calculation of flux additions for this practice:**

The MgO required for this FeO content (33%) in the slag is around 9% as seen in Figure 6. If you are aiming to have a B3 slag basicity equal to 1.8, (CaO% / SiO2% + Al2O3%) for good foaming and refractory protection you must have a MgO content around 10% based on Figure 3. If you are in the range of 9% to 11% for your MgO you can expect to have good protection of the furnace refractory accounting for slag FeO and slag basicity. You can now back calculate from slag analysis.

If you know how much lime you currently add to the furnace as a practice you can get this ratio. The total slag mass can be determined using chemical analysis. This can be done utilizing the following formula:
Total Slag Mass = \frac{(\text{High Cal Lime lbs} + (0.6 \times \text{Dolomitic lime lbs}))}{\text{CaO \% x-ray analysis}}

- Say you added 6,000 lbs of high calcium lime and 6,000 lbs of dolomitic lime as your current practice. The x-ray analysis of the CaO content is 30%. You calculate 
  \((6000 + 0.6(6,000)) = 9,600 \text{ lbs CaO} / 30\%\) to get 32,000 lbs of slag.
- If the analysis shows 15\% SiO\textsubscript{2}, you would now know the slag contains 4,800 lbs of SiO\textsubscript{2}. If Al\textsubscript{2}O\textsubscript{3} was 6\%, then the slag contains 1,920 lbs of Al\textsubscript{2}O\textsubscript{3}. This is related to your scrap mix.
- Now to get the correct MgO requirement you would keep the total slag mass of 32,000 lbs x 10\% MgO requirement = 3,200 lbs of MgO.
- Using dolomitic lime you would take 3,200 lbs / 40\% MgO to get 8,000 lbs of dolomitic lime needed. Now 8,000 lbs dolomitic lime x 60\% CaO = 4,800 lbs of CaO that is available from the dolomitic lime for your total CaO requirement.

How much total lime do you need?

You need to know what your aim basicity ratio:

- Take the x-ray analysis of SiO\textsubscript{2} + Al\textsubscript{2}O\textsubscript{3} = 21\% \times 32,000 \text{ lbs of slag} = 6,720 \text{ lbs of acidic oxides.}
- CaO required for an aim 1.8 B3 ratio = 6,720 lbs \times 1.8 \text{ ratio} = 12,096 \text{ lbs of total CaO.}
- Subtract the CaO from dolomitic lbs used = 4,800 lbs CaO from the total CaO lbs 12,096 lbs required to get the aim 1.8 ratio and you will need 7,296 lbs of high calcium lime!

The total flux needed to meet the slag requirements is 8,000 lbs dolomitic lime and 7,296 lbs of high calcium lime!
What is the summary of this exercise?

- The aim $B_3$ basicity of your slag = 1.8. This means that the calculated amount of lime (CaO) that is associated with the amount of silica (SiO$_2$) and alumina (Al$_2$O$_3$) produced from oxidizing your scrap to achieve this is 12,096 lbs of CaO. You will produce about 32,000 lbs of slag.

- The oxygen of the steel is based on the tap carbon of 0.023% carbon that is related to 750 ppm oxygen. At this oxygen level you will get about 33% FeO in the slag. This means that the MgO that is soluble in that amount of FeO is around 10% MgO. With 32,000 lbs of slag and 10% MgO requirement you will need 3,200 lbs of MgO.

- The total high calcium lime needed is 7,296 lbs and the total dolomitic lime needed is 8000 lbs. If this were a blended product you would have about 21% MgO in the lime blend and get about 10% MgO in the slag.

**Actual furnace conditions:**

Slag conditions vary on start up heats versus following heats. You are starting fresh with fluxes in a start up heat to meet what is required by the end of the heat.

When you leave slag in the furnace after tap for successive heats, you are starting with some slag that has these conditions to start with for the new heat. So, you have to consider additions of fluxes during the heat to meet the scrap melting rate along with the carryover slag that was left in the furnace.

Maintaining good oxygen control to keep FeO levels constant and additions of fluxes to meet melting rate will help maintain good slag conditions. Each crew needs to follow guidelines to work at achieving consistency in practice and results.
Keep points to remember for furnace slags:

- Four variables affecting slag are basicity, FeO content, MgO content and temperature.
- The lower the slag basicity, MgO requirement is higher for protection.
- The higher the slag basicity, the later the slag will foam.
- FeO is the primary fluxing agent. Too much FeO, slag is thin and won’t foam well. It is related to excess oxygen - balance carbon and oxygen practice.
- Adjustments may be required during the heat.
- Best to add some dolomitic lime to heel left in furnace then balance of fluxes based on melting rate.

Ladle slags for secondary metallurgy treatment:

The secondary process, which is seen in ladle furnaces and ladles at stir stations is a reduction process stage of steelmaking. The reduction phase of steelmaking is designed to remove dissolved oxygen produced during the oxidation stage in the electric arc furnace.

![Fig. 7. Ladle furnace for metallurgical treatment of steel after the EAF – Reduction Process](image-url)
How is ladle slag generated?

- Carryover slag from the furnace – high in FeO and MnO.
- Additions from fluxes such as lime, dolomitic lime, CaF2 or sand.
- Alloy additions for deoxidation creates oxides that float to top of ladle.
- Ladle coverings such as burnt rice hulls or basic materials.

Types of ladle deoxidation:

The initial addition of alloys during the tapping of steel from the furnace to a ladle is called precipitation deoxidation. That is because alloys such as ferrosilicon and aluminum combine with the dissolved oxygen in the liquid metal to form SiO2 and Al2O3 that becomes solid particles and precipitates out of the steel. This has to be removed by inert gas stirring. These solid particles are called “inclusions” and are not liquid at steelmaking temperatures. There are other types of inclusions that remain liquid at these temperatures but solidify during cooling. These include manganese sulfides and manganese silicates.

After the “deoxidized” steel arrives at the ladle furnace or stir station, the slag still contains dissolved oxygen in the form of FeO and MnO relating to slag carry over from the electric furnace. This higher oxygen slag can affect the oxygen content of the steel. This slag has to be treated with deoxidizers to reduce the oxygen activity of the slag so that the oxygen activity of the steel can be lowered without the additions of more alloys, which produces more inclusions. This reduction process is called diffusion deoxidation.

What are the advantages and disadvantages of each type of deoxidation?

<table>
<thead>
<tr>
<th>Precipitation Deoxidation</th>
<th>Diffusion Deoxidation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Advantages</strong></td>
<td><strong>Disadvantages</strong></td>
</tr>
<tr>
<td>Quick reaction time</td>
<td>Creates inclusions</td>
</tr>
<tr>
<td>amount</td>
<td>to lower oxygen</td>
</tr>
<tr>
<td>Simple to perform just</td>
<td>levels in ladle &amp;</td>
</tr>
<tr>
<td>additives</td>
<td>hard to remove.</td>
</tr>
<tr>
<td>add alloys.</td>
<td></td>
</tr>
<tr>
<td>slower.</td>
<td></td>
</tr>
</tbody>
</table>

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Slag properties and chemistry are important to lower sulfur levels and trap inclusions transported to the slag. Various steel quality levels require different conditions in slag requirements. Special Bar Quality is treated somewhat differently than the quality required in Merchant Bar Quality. There are some common aspects of secondary slags that are constant for either grade. Rebar grades require minimal conditioning and is geared more towards refractory protection than reduced inclusions and desulfurization requirements.

The following conditions will address the higher quality levels and the slag conditions that influence those grades of steel.

**What makes a good ladle slag?**
The following four conditions optimize the required slag for ladle metallurgy:

- **Limit furnace slag carry over to the ladle**
  High in FeO & MnO which are corrosive to ladle brick and adds oxygen to the steel. Influences pinhole formation in the steel.

- **Basic slag of 2.5 or higher – B5 ratio with 8 % MgO for refractory**
  Still fluid, not watery – must be creamy – use slag fluidizers or lime

- **Reduce FeO and MnO to 1% or less**
  Use deoxidants such as calcium carbide, aluminum, etc.

- **Maintain good slag depth with lime and blended lime to enhance Desulfurization.**
  Minimum 20 lbs/ton required for this process for removal of inclusions and good temperature control during inert gas stirring.

**What useful properties does slag have in ladle refining?**

- It insulates the bath, reduces temperature losses
- It desulfurizes the steel
- It helps control the types of inclusions and traps them in the ladle.
- It controls the steel oxygen levels and chemistry of the steel.
- Can protect steel from oxygen and N2 pickup. It can influence H2 pickup.
- It protects the ladle from arc flare and refractory erosion.
White Slag Practice:

The term *white slag* refers to the physical appearance of a properly deoxidized slag that will control the dissolved oxygen levels of the steel and cleanliness of the steel. The final slag color will get its color from the amount of reducible oxides in the slag. When a slag is completely deoxidized only the so-called *white oxides* remain giving the slag its appearance.

The following table shows this relationship of color and type of oxides:

<table>
<thead>
<tr>
<th>White Oxides</th>
<th>Dark Oxides</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaO</td>
<td>FeO</td>
</tr>
<tr>
<td>MgO</td>
<td>MnO</td>
</tr>
<tr>
<td>SiO₂</td>
<td>Cr₂O₃</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td></td>
</tr>
<tr>
<td>CaF₂</td>
<td></td>
</tr>
</tbody>
</table>

Make the slag first!

The following parameters are needed to assure a slag that will get the job done for higher quality steels:

- Higher volume of artificial slag materials for desulfurization and insulation properties.
- Correct blend of fluidizers including CaO, MgO, CaF₂ and SiO₂ as needed to produce a creamy slag.
- Deoxidize the FeO & MnO using calcium carbide so that slag will not transfer the oxygen activity to the deoxidize steel. Lowered oxygen activity of the slag is needed for desulfurization and control of chemistry in the steel. Manganese and phosphorous can be reverted to the steel if furnace slag carryover is seen.
- Proper inert gas stirring conditions for controlling desulfurization, alloying and rinsing of inclusions from the steel.

Control of dissolved oxygen using white slag practice:

As mentioned before about the balance concept in steelmaking, the same is seen in reducing the oxygen level in the steel by reducing the oxygen level in the slag. The following graph shows the ideal dissolved oxygen levels by carbon content to avoid pinholes in the solidified steel:
Fig. 8 Relationship of dissolved oxygen and pinhole formation with carbon content

The oxygen content is controlled through a deoxidized slag with proper stirring. Pinhole formation can be reduced if nitrogen and hydrogen levels are maintained at lower levels. Pinhole formation is influenced by the amount of carbon present to make a CO bubble that can be trapped in solidifying steel at the caster. These pinholes can cause surface defects in the finished product. This relationship is affected by nitrogen, hydrogen, oxygen content at a certain carbon level. The lower the carbon the less likely a pinhole can be formed, thus allowing higher dissolved oxygen contents. The equation below represents this relationship:

$$P_{CO} = P_{H2} + P_{N2} + P_{O}$$

What this says is that the partial pressure to form a CO bubble is related to the combined partial pressures of the other gases. If nitrogen levels are higher, then the oxygen content of the steel must be lowered and the hydrogen content must be low. Therefore, a final ladle carbon content of 0.08 % with 65 ppm of nitrogen requires the dissolved oxygen to be below 45 ppm for SBQ and 70 ppm for merchant bar, which allows some surface imperfections.
Desulfurization:

Sulfur removal for most grades of steel is important for physical properties of the steel. Sulfur can be a bad actor by reducing the steel's ability to resist fracturing and cracking. The 5 primary factors that affect desulfurization are:

- Enough basic slag volume and chemistry to create a *creamy slag* affects sulfur capacity of the slag to remove sulfur.
- Low FeO in the slag and dissolved oxygen in the steel
- Arrival sulfur content of steel in ladle
- Desulfurization is favored by higher temperatures but this is limited at the ladle furnace. When the temperature increases sulfur removal will increase as long as oxygen levels in slag and steel are low.
- Good stirring to promote slag and metal interaction.

The reaction that takes place during desulfurization can be shown below:

\[
2\text{CaO}_{(\text{slag})} + 3\text{FeS}_{[\text{steel}]} + \text{CaC}_2(\text{slag}) \rightarrow 3\text{CaS}_{(\text{slag})} + 3\text{Fe}_{[\text{steel}]} + 2\text{CO}
\]

In summary, key factors for good ladle treatment:

- Type of ladle refractory – basic ladles for higher qualities.
- Stirring device – create slag / metal mixing
  - Bottom stir plug
  - Stir rods
  - Electromagnetic stirring – desulfurization more difficult
- Type of artificial slag utilized and amount utilized
  - dependent on whether making aluminum killed or silicon killed steel
  - enough volume and fluidity for desulfurization and trapping inclusions
  - produce a white slag to reduce oxygen activity of slag
- Inert gas rinse following final addition to remove inclusions
- Temperature control
References:


D. Schroeder, “Charge Design Calculations with Slag and Energy Balancing” AISE Conference 2002