

Chapter IV

AOD Processing

Some claim the introduction of the AOD Process for the refining of specialty steels and alloys represents the most significant advance in the manufacture of these materials. The five and six-hour heat times associated with producing a final carbon content below 0.030% in the electric arc furnace have been replaced by routine production of extra-low carbon (ELC) stainless heats in less than two hours in the AOD vessel.

The production of an aircraft quality low-alloy heat in the arc furnace, with its sluggish slag-metal reactions, has been replaced by a four-minute reduction (deoxidation) stir in an AOD vessel. Twenty years ago, extensive furnace deoxidation procedures, coupled with lime-magnesium injection, were required to make 0.005% maximum sulfur. Today, even 0.001% sulfur can easily be produced with AOD.

Given below are generalized processing techniques for stainless steel and for low-alloy EAF-AOD duplexing. These are not intended as rigorous practices, but rather to give an overview of AOD procedures. It should be noted that AOD vessels accept molten metal transfers from not only electric arc furnaces, but have also routinely treated molten steel (or ferroalloys) from: induction furnaces, LD (or BOP) converters, and submerged arc smelting furnaces. On an intermittent basis, metal from hot metal sources including blast furnaces and cupolas have also been refined in AOD vessels.

A. Stainless Steel

o Electric Arc Furnace (EAF)

Accurate end-point control begins in the EAF. That statement is not surprising, but it deserves emphasis. It is very easy to relax attention given to the electric furnace when an AOD vessel is introduced. The quality of the furnace charge is almost always decreased after the installation of an AOD unit, even while product specifications are being tightened. Raw materials charged to the furnace should be selected on the basis of least cost, AOD-refined steel. In general, alloying elements such as manganese, chromium, nickel and molybdenum are charged to melt in very close to specification requirements. The carbon content of the hot metal transferred to the AOD vessel will be a function of the scrap:alloy ratio which in turn is dependent on relative economics and/or residual element (e.g., phosphorus, copper, cobalt) requirements. EAF silicon levels at tap should be sufficient to ensure good metallic reduction but not so high to result in severe AOD lining wear; typical aim tap silicon contents range from 0.15-30%.

The objective for the EAF is to minimize metallic oxidation of chromium, manganese, iron, etc. during melt-down and provide a fluid bath as quickly as possible for transfer to the AOD. Oxygen can be used to assist in melting, bath homogenization, temperature increase and also to control silicon content.

Details of the electric arc furnace practice will vary from shop to shop depending on furnace configuration, heat size, charge make-up, and power costs. The bath temperature must be elevated to a level sufficient to provide hot metal in the AOD vessel at roughly 2800°F (1540°C). The degree of super-heat required in the EAF is a function of the temperature loss during tapping, transfer activities and charging

to the vessel. This again will vary by shop with the number of furnaces involved, transfer ladle refractory composition, and transfer ladle and vessel preheat. EAF tap temperatures between 3000°F (1650°C) and 3100°F (1700°C) are common.

A typical EAF practice would be to melt-down under a basic, reducing slag, followed by a chemistry sample to determine melt-down silicon level. Quite possibly the chemical analysis will be extensive to determine the level of tramp and residual elements and to verify that major alloying elements are within acceptance limits. An oxygen blow may be used to lower the silicon level and raise the temperature. The bath is heated to tap temperature and tapped into the transfer ladle.

o Transfer Ladle

Before transferring the molten metal to the vessel, the furnace slag is commonly removed as completely as practical. Slag carried into the refining vessel and not removed before decarburization will result in unpredictable final composition and will adversely effect AOD lining life.

Deslagging can be performed from either the furnace and/or the transfer ladle, depending on shop layout. If silicon is to be added for alloy recovery, then deslagging from the ladle is preferable, to take advantage of tap stream mixing. In some cases, arc furnace slag is transferred with the crude stainless steel into the AOD vessel and is first stirred for alloy recovery and then the slag is removed prior to the start of decarburization⁽⁶⁴⁾.

After slag removal, the ladle plus metal and any remaining slag is weighed. An accurate weighing method is desirable since this measurement will directly affect the subsequent processing calculations.

At some point during the transfer cycle, a chemistry sample is obtained. This complete analysis is used as the starting composition for AOD processing.

o AOD

Stainless production in the vessel can be broken into three phases as summarized below:

- i) Decarburization
 - From any carbon level to specification level
 - Control of bath temperature
 - Additions to adjust heat weight, bath and slag composition, and control temperature
- ii) Reduction/Desulfurization
 - Recover virtually all oxidized metallics
 - Degas
 - Sulfur control to any level from 0.001% to 0.020% with a single or double slag practice as appropriate
- iii) Trim
 - Minor adjustments to chemistry and temperature

i) Decarburization

Once the heat has been transferred to the AOD vessel, bath temperature is usually sampled. Based on the starting temperature, chemistry and weight, a series of calculations to guide processing is made either by the operator or by computer. Results of these calculations include:

- Amount and timing of alloy additions
- Duration of a given oxygen:inert gas ratio
- Inert gas selection (nitrogen or argon)
- Estimated quantity of reduction material required

The above determinations are made within the constraints of temperature control below some upper limit (e.g., 3100°F or 1700°C), minimization of metallic oxidation, and composition adjustments to aim analysis.

Figure 9 displays a typical (18 Cr) stainless heat manufactured via the AOD process. The initial blowing period is performed with a ratio of oxygen:inert of 3:1. At the end of this blow period, some additions (perhaps for alloying and/or slag adjustment) have been made as evidenced by the temperature drop. Note that the carbon level at the termination of this step is roughly 0.30%, chromium losses are negligible and temperature is acceptable.

Continued blowing with the 3:1 ratio would result in excessive metallic oxidation and attendant temperature rise. Therefore, for the next interval of carbon removal a "leaner" (more dilute) oxygen ratio is used. As Figure 9 shows, carbon is taken from the end-of-3:1 level to about 0.10% using an oxygen:inert gas ratio of 1:1. Again, temperature rise and chromium oxidation are minimal.

The third and final decarburization ratio in our example employs an oxygen:inert gas ratio of 1:3 down to final carbon level. For a given

temperature and chromium content, isothermal removal of carbon from lower levels (e.g., 0.06%) requires more dilute oxygen injection than 1:3.

The use of a top lance during decarburization is discussed in a subsequent chapter and shown in Figure 1. The use of air as a partial substitute for nitrogen, first practiced by Outokumpu and later adopted by Allegheny Ludlum⁽⁶⁵⁾ has proven economic only in special circumstances.

At some point prior to the end of the decarburization period, a sample for carbon analysis is usually obtained. This carbon check is used to verify and fine-tune the original end-point calculations. Based on this updated oxygen requirement, a precise determination of reduction additions and fluxes is made.

As shown in Figure 10 the final nitrogen can be easily increased by controlled substitution of nitrogen for argon during the blow. There are several motivations for a deliberate increase in nitrogen content: (1) to decrease argon consumption on grades with a liberal N specification, (2) to control ferrite content while minimizing nickel content, and (3) to produce high-nitrogen (nearly up to saturation) austenitic stainless grades.

ii) Reduction/Desulfurization

After the aim carbon level is achieved, alloys and fluxes which promote the recovery of any oxidized metallics are added (in batch) to the vessel. The amount of reduction material (usually silicon ferroalloys or aluminum) required is accurately determined because the amount of oxygen consumed by metallic oxidation may be precisely calculated since no oxygen escapes from the vessel un-reacted. The amount of metallic oxidation is determined by the difference between total oxygen consumed and that attributable to silicon and carbon oxidation.

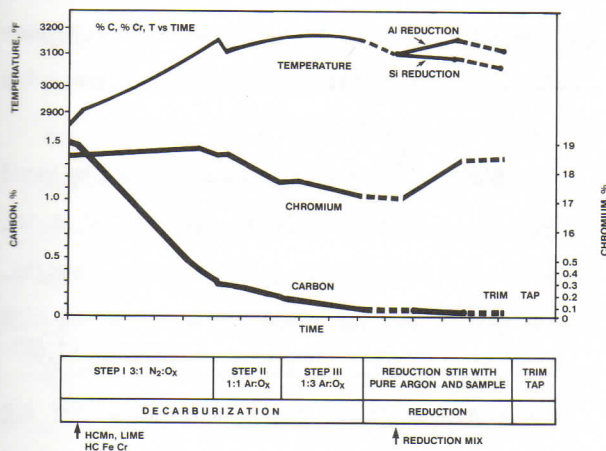


Figure 9. Schematic of stainless steel refining cycle.

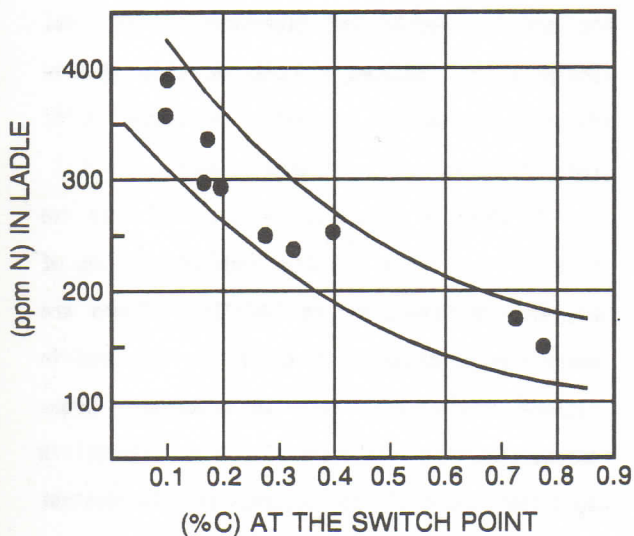
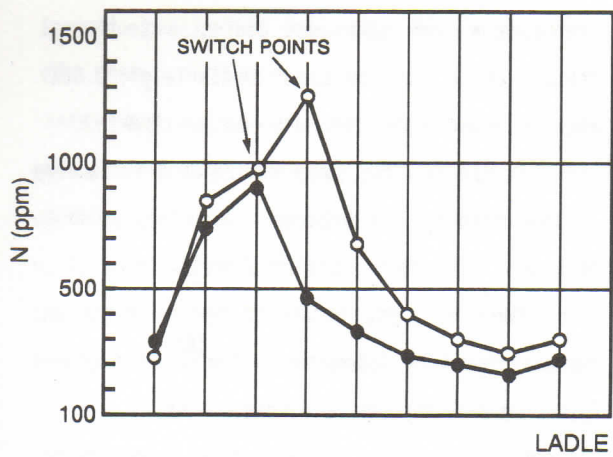


Figure 10. Nitrogen's dependency on timing of switch to argon. Applies to 18Cr-8Ni steel.

A calculated amount of fluxes (all or mostly lime) is added with the silicon (and Al) to obtain the desired slag basicity (V-ratio). Basicity is usually balanced between the desire for a high level to maximize efficiency of reduction reactions and the need for a low level to minimize slag volume in order to maximize chromium recovery.

The reduction mix may contain, in addition to reducers and fluxes, alloys and/or scrap for the primary purpose of temperature adjustment. The reduction mix is usually stirred with inert gas for a period sufficient to allow completion of

oxidation-reduction reactions and slag formation, usually 4 to 8 minutes, depending on vessel size and stir rate.

At the termination of the reduction stir, if very low sulfur levels are required, or if the initial sulfur content was quite high, it may be necessary to add a second, very basic ($\text{CaO/SiO}_2 > 2$) slag mix. This desulfurization slag is added after the original reduction slag has been decanted. Again, a short stir period promotes quick slag formation and rapid sulfur removal.

Following the stir period(s), the bath is sampled for chemistry and temperature. Preparations for tapping the AOD vessel (e.g. teeming crane availability, caster availability, teeming ladle, ladle additions, etc.) are made during this wait for chemical analysis.

iii) Trim

Small adjustments in composition are made based on the after-reduction chemistry. Depending on the types and amounts of materials necessary, the addition can be either stirred in the vessel and/or added in the tap ladle.

Temperature adjustment may also be required at this time. Cooling, depending on the vessel size, can be accomplished by scrap/alloy/flux additions and/or stirring. Heating the bath involves the combustion of a fuel element (e.g., aluminum or silicon) with gaseous oxygen. Because of the predictability of the process, tap temperature control of $\pm 5^\circ\text{C}$ is common.

Modern AOD practice is characterized by rapid heat times, achieved through the use of a top lance, and occasionally a sublance for sampling, and long refractory campaigns resulting in high productivity and low refining cost^(64,66,67,68)

For a discussion of one example of modern AOD refining practice, please see the appended reference by Ikehara, Kosuge, Ariyoshi and Hidaka

which describes Nippon Steel's operation⁽⁶⁸⁾. The flexibility of the AOD process is displayed by Pacific Metals refining of liquid high carbon ferrochromium and ferronickel to low carbon stainless steel in their 30 ton AOD vessel. A complete description of this operation is covered in the appended reference by Yamada, Azuma, Hiyama and Nishimae⁽⁶⁹⁾. AOD operation in a specialty steel shop, producing both stainless and tool steels, often demands varying heat sizes and severe compositional restraints which are reviewed in the appended reference by Delans and Byrnes⁽⁷⁰⁾.

The use of small AOD vessels in foundries, especially investment foundries, leads to special operating concerns, including the need for a movable vessel to minimize the heat loss associated with transfer. A description of small vessel operation is covered in the appended reference by Sarlitto⁽⁷¹⁾.

B. Low-Alloy

The melt-down of EAF charges of carbon/low-alloy grades for subsequent AOD refining can be performed with one of two techniques: (1) completely open, with the addition of ore, scale or oxygen to dephosphorize (and oxidize chromium and manganese), or (2) dead-melted for the retention of all metallics. In the latter case, composition is controlled to specification aims for most elements, with the exception of carbon and silicon. The choice between these EAF procedures depends, in part, on scrap composition relative to specification requirements, but mainly on the need for dephosphorization. The transfer ladle practice for these grades is similar to that described for stainless transfers. Slag removal prior to vessel charging is especially critical if reversion from an oxidizing, phosphorus-bearing slag is to be avoided.

Starting carbon and silicon contents in the vessel as well as the timing of adjustments to the starting carbon and silicon are determined by heat size, EAF practices, transfer temperature, composition and quality requirements, and other shop-specific circumstances. For these grades, the blowing schedule is simplified to a single, oxygen-rich (3:1) ratio. This ratio is used for two purposes:

- Decarburization (generally at least 0.2 - 0.4% carbon for degassing)
- Temperature elevation through oxidation of a fuel element

After decarburization and initial fueling, a "reduction" desulfurization mix (if necessary) is stirred for two to three minutes. Following sampling of chemistry and temperature, final adjustments to chemistry and temperature are made and the heat is tapped. Typical single-slag low-alloy heats, as shown in Figure 11, have AOD heat times of 25-40 minutes.

Temperature control during AOD refining is accomplished by controlling the peak temperature at the end of the oxygen blow (see Figure 11). Data in Figure 12⁽⁷²⁾ for a 40-ton vessel indicate that on 95% of AOD heats sufficient temperature is reached at that stage to enable the heat to coast

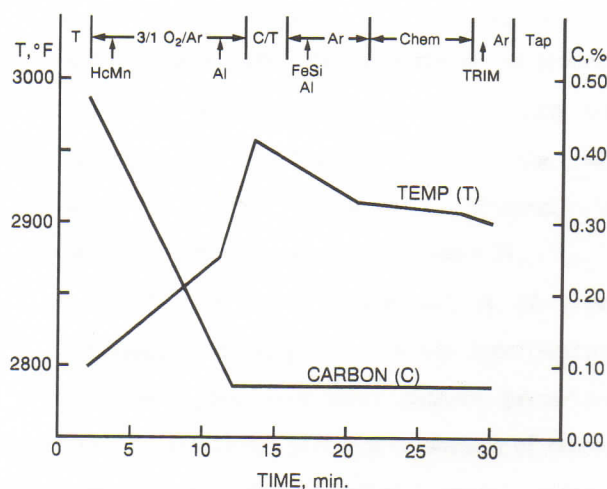


Figure 11. Schematic of carbon/low-alloy refining cycle.

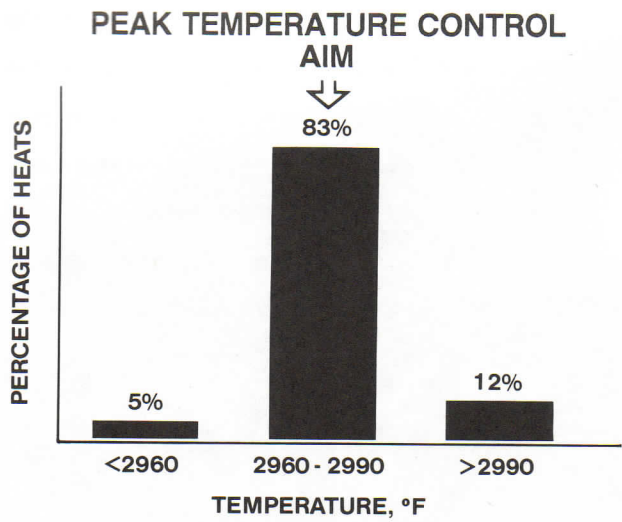


Figure 12. Peak Temperature Control. (Andreini and Farmer (77))

down to tap temperature. Only 5% of the heats, plus any heats which are delayed by other problems in the shop such as a crane outage, need to be reblown. For small vessels, especially those smaller than 10 tons, a reheat step prior to tap may be required. Final teeming temperature control of $\pm 8^{\circ}\text{F}$ is achieved on carbon and low alloy steels ingot teemed at 2816°F .