Metallurgical and Economic Considerations of the AOD and VOD Process

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A variety of influencing factors must be considered in order to come to a decision which process, or which route (duplex or triplex) is the proper choice. It is important to know that the processing of stainless and special steels calls for a modern mass production with a strong focus on ergonomics and resource efficiency.

1 INTRODUCTION

Nowadays, the Argon Oxygen Decarburization (AOD) and the Vacuum Oxygen Decarburization (VOD) processes are the dominating methods for refining of stainless steel with low carbon contents. An overview about the 4 most important stainless steel groups is shown in **Figure 1**.

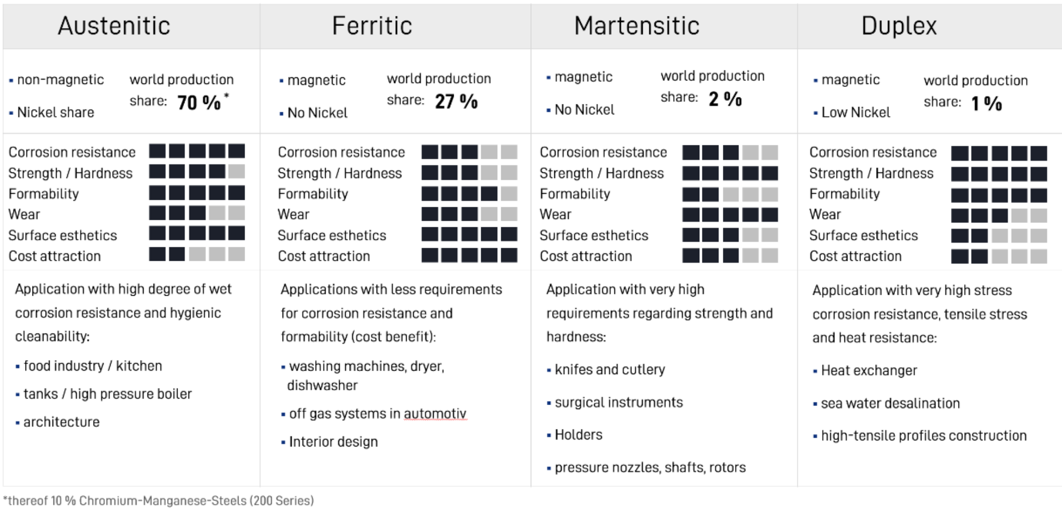

Figure 1: Comparison of different stainless steel types (according to [1])

A great paper about stainless steel refining was published by Richard J. Choulet. He summarized the development of these two processes, which revolutionized stainless steel production as follows [1]:

As early as 1954, W. Krivsky experimentally investigated the carbon-chromium temperature relationships when melting ferrochrome in the laboratory. In these experiments, oxygen was blown onto the surface of baths of molten chromium alloy under isothermal conditions. To control the temperature, he added argon and found that he could decarburize the melt to a low carbon content without excessive chromium oxidation. These findings led to plant-scale experiments injecting argon/oxygen mixtures by lance into the arc furnace between l958 and l962, and the first successful AOD heat was made in October 1967 in a modified 15-ton ladle.

The VOD process was developed by Witten in Germany between 1962 and 1967 in connection with the installation of a ladle vacuum degassing system. First attempts were made using iron ore for decarburization. Later premelting took place in the arc furnace and oxygen was top blown onto the bath surface in the degassing ladle.

The main goals of both processes are decarburization, desulphurization and the adjustment of the target nitrogen content. However, the necessary amount of oxygen for decarburization leads to undesirable losses of alloying elements, in particular chromium but also of Ti, Al, Si and Mn. Therefore, a reduction from the slag as well as additions of slag formers to ensure a good desulphurization after slag reduction must be carried out, which leads to additional costs.

Based on a paper presented at *the 8th European Stainless Steel Conference 2015* in Graz [3], the following chapters give an overview about the metallurgical and economic issues regarding stainless steel making using the AOD and VOD process. Firstly, chapter 2 shortly describes the two stainless steel making routes. Chapter 3 summarizes a comparison of the AOD and VOD process with respect to general, operating and metallurgical parameters.

2 STAINLESS STEEL-MAKING PROCESS ROUTES

Generally, the relevant literature as well as the linguistic usage deals with two different stainless steel making process routes: (1) duplex and (2) triplex refining. The former describes the melting in the electric arc furnace (EAF) followed by refining in a converter, the latter describes the process route where the EAF and the converter refining is extended by a vacuum refining process. However, based on a variety of developments for stainless steel making in the past, the available processes can also be categorized into three groups:

(1) the converter processes,
(2) the converter with vacuum processes and
(3) the vacuum processes [3].

In this context, the present study understands the EAF – (LF) – AOD and the EAF – (LF) – VOD as the duplex refining route, and EAF – (LF) – AOD – VOD as the triplex refining route (see **Figure 2**).

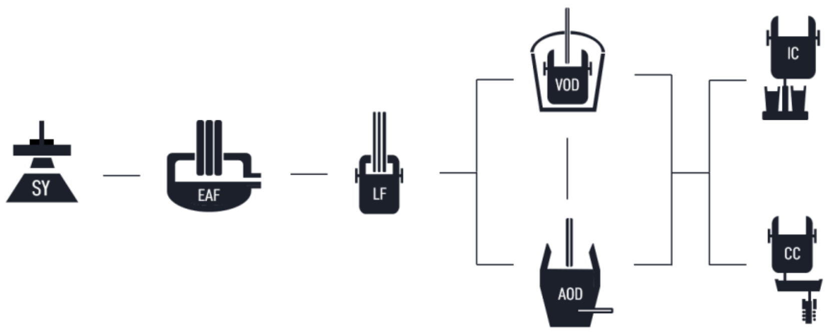

Figure 2: The different stainless steel-making routes

3 A COMPARISON OF THE AOD AND VOD PROCESS

3.1. Decarburization Strategies

The economics of material costs and the need to recycle chromium steel scrap dictate that stainless steel is mainly produced by processes which involve the removal of carbon from liquid iron in the presence of chromium. Low carbon contents are necessary to achieve the corrosion-resistance in stainless steels. Stainless steel decarburization however must minimize the oxidation of chromium, which can be realized via three different strategies:

(1) temperature,
(2) dilution and
(3) vacuum.

The first approach was used by the EAF stainless steel making before the duplex refining processes was developed and is based on the accepted fact that with increasing temperature the equilibrium carbon content deceases (i.e. at particular chromium content). The drawbacks are obviously operational difficulties and high costs [2-5].

The AOD process (or other similar converter processes) uses the dilution approach. Here, the injection of inert gas leads to the effect of lowering the partial pressure of CO, pCO, in the liquid. Thus, higher chromium contents are in equilibrium with lower carbon contents. The VOD process (or in general the application of vacuum to the melt) also uses the effect of lowering the pCO in the liquid and is in particular effective when the required carbon content must be very low. The establishment of both processes – the AOD and VOD process – was directly linked with two big technical developments, the industrial production of liquid argon and nitrogen and the availability of powerful vacuum-pumps.

3.2. Influencing Factors to be Considered

What is now the proper choice with respect to AOD and VOD? A serious answer to this question is apparently not possible without taking into consideration a variety of influencing factors. According to R. J. Choulet and I. F. Masterson [5], the choice of the most practical and economic process route for stainless steel making depends on (1) the available raw materials and costs, (2) the productivity requirements, (3) the product mix, (4) the existing shop equipment and logistics and (5) the capital and operating costs.

Besides these factors, other important factors are general business conditions, company financial status, company mergers and/or consolidation of steelmaking facilities, plant closures, competency of available manpower as well as social and political concerns [5].

3.3. Comparison with Respect to General and Operating Parameters

Generally speaking, AOD has more capacity in comparison to the VOD process, but the efforts are higher and environmental effects must be considered more than in comparison to operating a VOD. AOD is limited in final carbon and nitrogen contents by several reasons, but more flexible regarding the carbon start content. **Table 1** summarize some important technological parameters of both processes.

Table 1: Comparison of different technological parameters

	Oxygen Supply	Inert Gas	Min. p_{CO} with O_2 use	Productivity(~15 %Cr)	Environment
	+ Max. 1,25 m^3/(t.min)	+ Max. 1,25 m^3/(t.min)	+ 0,1 bar	+ Very High at 2.0 – 0.4 %C + High at 0.4 – 0.02 %C + Poor below 0.02 %C	+ Bigger amount of slag, + Emissions from tapping and charging must be collected + Noise of top-lance and dedusting, + Use of off-gas energy in steam generation possible
	+ Max. 0,3 m^3/(t.min)	+ Max. 0,3 m^3/(t.min)	+ < 0.05 bar	+ Poor > 0.4 %C + High at 0.4 – 0.01 %C + Poor below 0.01 %C	+ Less slag, + No emissions, + Noise of pumps, + Use of off-gas energy in steam injector possible.

3.4. Comparison with Respect to Metallurgical Parameters

Regarding metallurgical issues, the achievable results are as illustrated in **Table 2**. It is important to note that these values do not represent limits which cannot be exceeded, but the efforts to go beyond these values dramatically increase. This also leads to a decrease in productivity and the process becomes riskier. Considering for example the carbon content, the adjustment of this parameter is more accurate in the VOD process, since the carbon pick up from the ladle occurs during treatment under the control of the operator. The major advantage of the VOD process is the decarburization to a low carbon level with low argon consumption and low oxidation of chromium. It is obvious that the lower the chromium oxidation, the lower the consumption of reduction elements for recovering chromium from slag. Furthermore, the pickup of nitrogen and oxygen from air, which is associated with tapping of the converter, is more or less eliminated when using the VOD process. This can easily be explained by the use of the ladle for the teeming of steel. However, the VOD process is less flexible than an AOD with respect to raw materials usage. As shown in Table 2, typical additions of raw material to the VOD process are around 5% of the tap weight, compared to up to 20 % in the AOD process. Moreover, typical treatment times of the VOD process are 50 to 70 minutes with a start carbon content of ~ 0.3 to 0.4 wt,-%, compared to 40 to 60 minutes in the AOD process, which allows higher carbon start content (1.5 to 2.5 wt.-% C). Considering this fact, it is also clear that this additional time results in difficulties to ensure the continuous casting sequence [2-5].

Table 2: Comparison of different metallurgical parameters

	$[C]_{Min}$ and $[N]_{Min}$ Content	$[H]_{Min}$ Content	[Cr] Content	Stirring Effects)	Possible Material Addition
 AOD	+ < 200 ppm before tapping	+ < 2 ppm before tapping	+ 5 – 25 wt.-% (high $[C]_{End}$ max. 50 %)	+ Superior	+ 0 – 20 %
 VOD	+ < 100 ppm in casting ladle	+ < 1 ppm in casting ladle	+ 5 – 35 wt.-%	+ Limited	+ 0 – 5 %

The factors of availability and raw materials costs play a very important role during process selection. For example, high argon costs shift the economics of stainless steel production from the AOD to the VOD process. A low availability of scrap demands the use of more high-carbon ferrochrome, which results in a higher carbon load in the charge. High decarburization rates are beneficial in such a case. Lack of scrap may also prefer processes which are not thermally efficient when the scrap is used for cooling the bath [3]. On the contrary, the availability of blast furnace or Corex hot metal or expensive power supply may favor hot metal supply to AOD converters. This comes along with high start levels of carbon and silicon, which in turn promote a high converter blowing rate [5].

The requirement of high productivity was already mentioned and usually, a high productivity can be reached using converter processes. In this context, the production mix must be considered and plays an important role. Vacuum processes benefit the production of stainless steels with high chromium as well as ultra-low carbon and nitrogen alloyed steel grades. Argon consumption can also be reduced in this case. Grades which require ultra-low sulfur contents are generally produced by converter processes [2-5].

3.5. Comparison of Three Different Steel Grades

All the above factors are also reflected in **Table 3**, which lists three different types of stainless steel, their relevance to the geographical production location and the decision criteria for using AOD or VOD. In times of increasing requirements for stainless steels, VOD is the right supplement for existing AOD steel plants. AOD and VOD are always good options for Greenfield projects. Duplex and/or triplex melting can reduce costs by using cheaper raw material and increased productivity together with the highest flexibility with respect to raw materials, production capability and process flow.

Table 3: Comparison of three different steel grades

AISI-No.	C	Cr	Ni	Mn	N	Relevance	Decision Criteria	Process
304	0.07	18.00	9.00	1.00	0.10	Standard stainless steels (Europe)	Productivity Big market Use of high carbon Cr	AOD
204Cu	0.15	16.50	2.30	8.00	0.10	Standard stainless steels (Europe)	Productivity Big market Use of high carbon Cr	AOD
447	0.01	29.00	0.20	0.60	0.01	Superferitic Steel, High Corrosion Resistance Steels	Low C Low N Smaller market	VOD

4 SUMMARY

In the last century the stainless steel market changed from special application to mass production. Increasing production went parallel with the development of continuously improved materials. New steel grades as well as further developments of existing alloys such as Cr-Ni austenitic steels, Cr-Ni-Mo austenitic steels, ferritic Cr-steels and nowadays more and more Cr-Mn-Ni austenitic steels have been accompanied by advancements in metallurgical processing.

The present article discusses the metallurgical and economic differences as well as the advantages of the AOD and VOD process. We showed that a variety of influencing factors must be considered in order to come to a decision which process, or which route (duplex or triplex) is the proper choice. It was further illustrated that nowadays the processing of stainless and special steels calls for a modern mass production with a strong focus on ergonomics and resource efficiency. Both the AOD and VOD processes require an optimized plant configuration and an intelligent process automation system with metallurgical models and set-point control. The requirements for such a software system for process supervision, control and optimization will be summarized in a further article.

5 REFERENCES

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