

RECENT DEVELOPMENTS IN STEELMAKING AND CASTING

Norbert Bannenberg

AG der Dillinger Hüttenwerke
Postfach 1580
66748 Dillingen, Germany

Abstract

An overview of the chronological development of steelmaking and steelmaking processes is first provided. The current status of steelplant technology and foreseeable development trends are then outlined. Secondary metallurgy, in particular, has developed in recent years into an independent stage in the steelmaking process. Selection of appropriate processing routes correlating to the properties required in the steel make it possible to meet the high demands nowadays made on steel quality. A significant decrease in achievable contents has become possible in the past two decades in the case of the elements carbon, phosphorus, sulphur and total oxygen, in particular. Production of a product which is free of surface defects is the target in the continuous-casting process. The preconditions for production of a crack-free slab surface are assured by means, in particular, of the cooling strategy applied in the casting machine's secondary cooling zone.

Introduction

Steelplant technology has undergone rapid development in the past two decades. To answer the question of how steelplant technology will look in the future, an overview of developments, its present-day status, and, on the basis of this, an estimation of future developments, are provided.

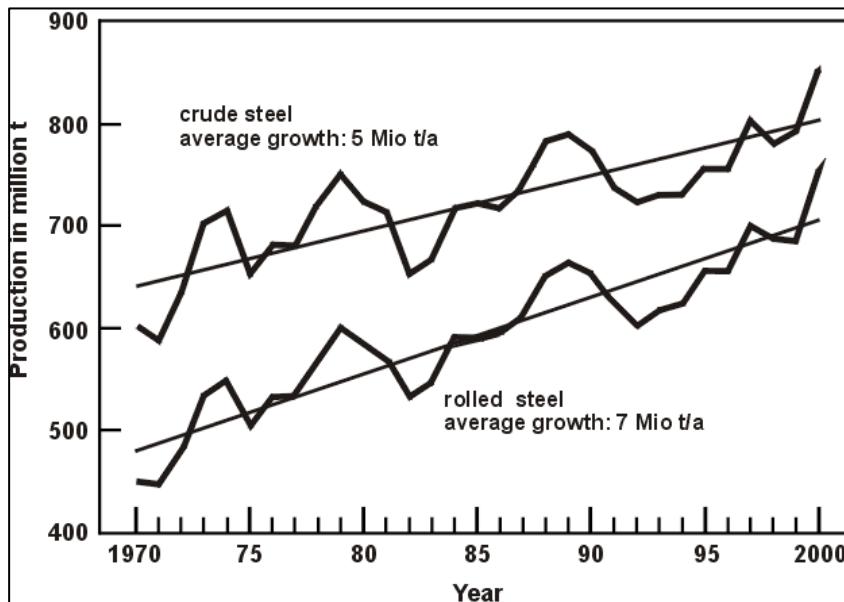


Figure 1: Development of the world-wide steel production.

An examination of world annual crude steel production shows that, with certain fluctuations, it has risen continuously throughout the last thirty years (Figure 1). Average annual growth was 5 million tonnes. The production of rolling steels also rose simultaneously, at a rate of 7 million t/a. The higher increase in rolling steel production compared to production of crude steel has been characterized by the increased use of continuous-casting technology which assures better steel yield. Whereas, fifty years ago, the Thomas (basic Bessemer) and the open-hearth processes were western Europe's dominant methods of steel production, the picture today is completely different (Figure 2).

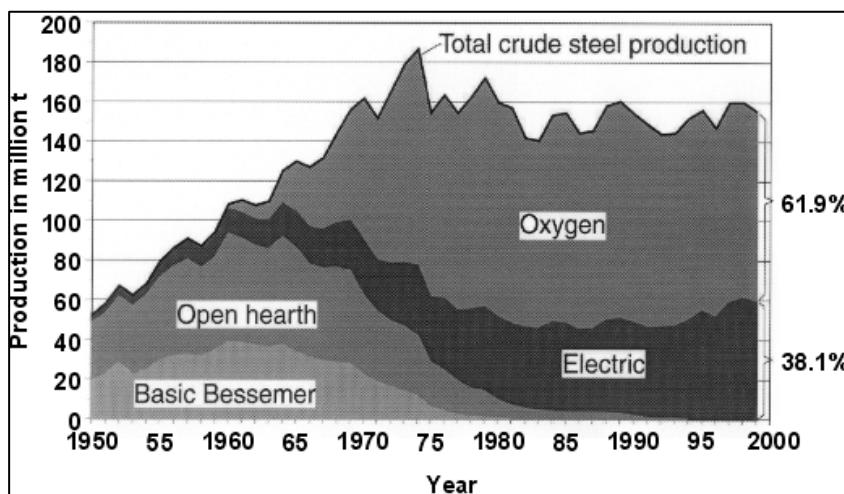


Figure 2: Crude steel production in EU (15) countries since 1950.

More than 60 % of present-day production of crude steel takes place in LD steelplants, and nearly 40 % in electric-furnace steelmaking plants. The Thomas and open-hearth processes no longer have any significance in western Europe. A similar trend has also occurred in worldwide steel production (Figure 3).

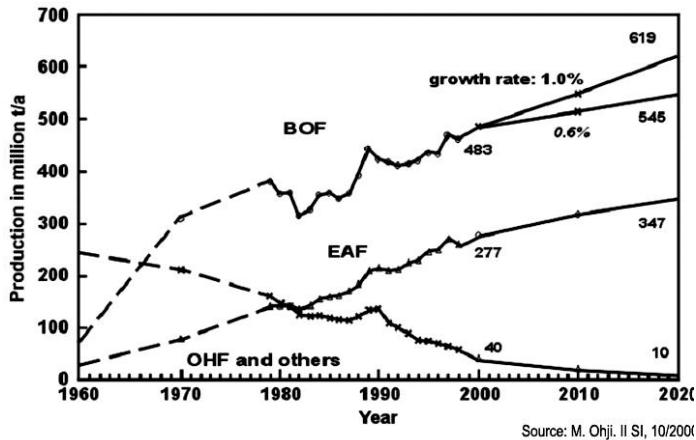


Figure 3: World-wide crude steel production by different production processes.

In the year 2000, the open-hearth and Thomas processes accounted for only 40 million t/a. Electric-furnace steel production's share has risen continuously throughout the past twenty years and has practically doubled in this period. Steelmaking using the LD route today remains the world's dominant steelmaking process, although its rate of growth in the past 20 years has been lower than in the case of electric steelmaking. An attempt at a forecast up to the year 2020 indicates that the open-hearth process will continue to lose significance, and will then make up a negligible portion of world steel production. The amount of steel produced using electric means will continue to rise, and the increase in world production of crude steel will also be borne by the LD process in the next twenty years. It is possible, on the basis of this forecast to predict a world crude steel production of 900 to 970 million t/a for the year 2020.

The shares of the various processes in world crude steel production are shown in Figure 4. It is clear that the electric arc furnace accounts for a good third of steel production, while now, and also in the future, about two thirds are produced using the LD route.

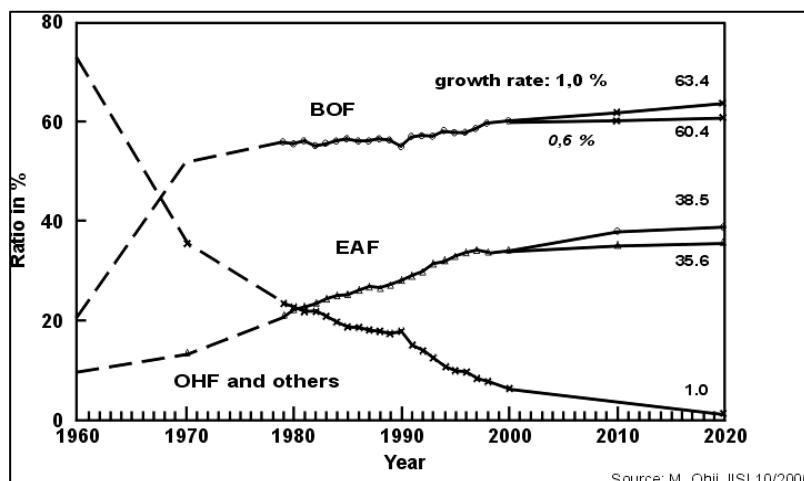


Figure 4: Ratio of world-wide crude steel production by different production processes.

Following the development of continuous-casting in the 1970's, developments in the field of steelplant technology in the last two decades have been shaped, in particular, by the increasing importance of secondary metallurgy. Vacuum technology, in particular, has made a decisive contribution to the significance of secondary metallurgy (Figure 5). Vacuum capacity in the 15-member EU has continuously increased in the last fifteen years, and it is now possible to vacuum-treat more than 80 % of steel production. Ladle furnaces for secondary metallurgy were first introduced into electric-furnace steelplants. The use of ladle furnaces in BOF steelplants has also steadily increased in recent years. More than 30 % of steel production in the 15-member EU can now be treated in a ladle furnace during secondary metallurgy. It can be assumed that, in the years to come, the percentage of vacuum capacities will continue to rise. The same applies to ladle furnaces.

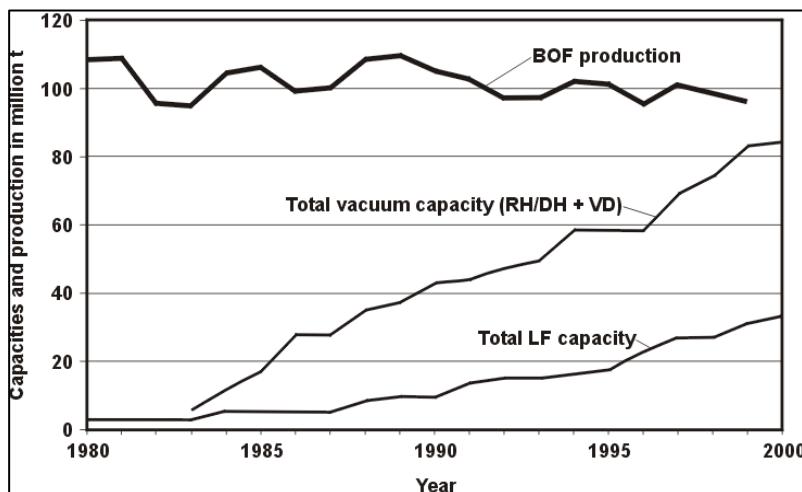


Figure 5: BOF-production, vacuum- and LF-capacities in EU (15).

Continuous-casting technology was developed in the early 1970's in Japan and Europe, in particular, and was then introduced to the steelplants (Figure 6). The proportion of steels cast using continuous-casting steadily increased correspondingly in Japan and Europe between 1970 and 1990. Saturation at a level of around 95 % has now been reached in both of these regions. A similar trend occurred with continuous-casting technology in the USA, with a time lag of 3 to 4 years, however. Here, too, the percentage of steels continuously cast now also amounts to some 95 %. A significant increase in continuous-cast production has only been observable in eastern Europe and the developing countries since 1990. The market share of the continuous-casting process will with certainty continue to rise in these countries in the coming years. On a world observation, this signifies that around 85 % of steel production is nowadays continuous cast. This figure will probably rise to above 90 % in the next few years.

So much for a general overview of the main trends in the field of steelplant technology and for predictions of future developments. We should now examine the steelmaking process in detail.

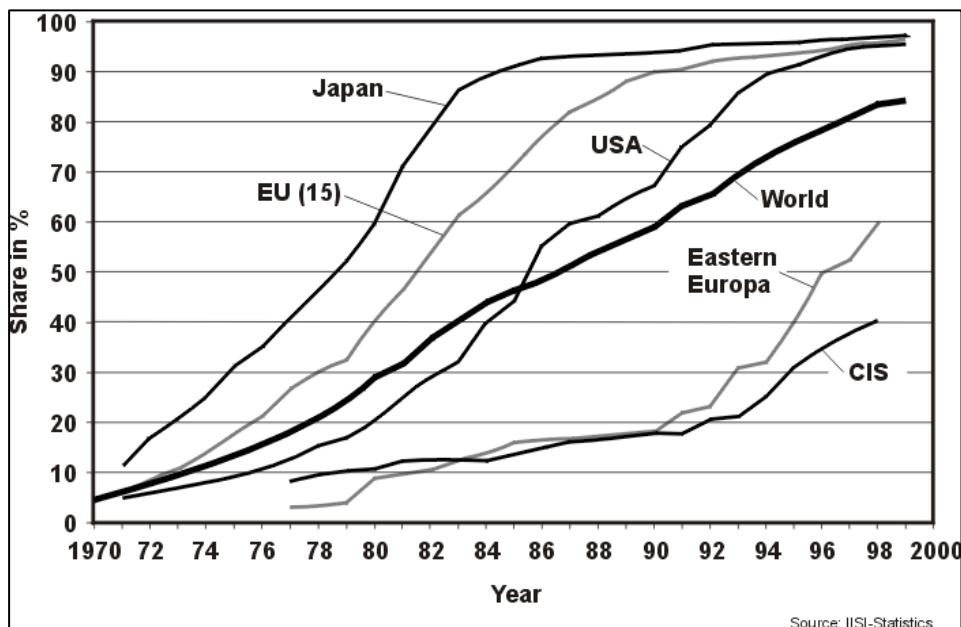


Figure 6: Share of continuously cast output by region.

Development of Steelplant Technology

Previously, the steelplant process in an LD steelplant was dominated by the two process stages of the LD converter and continuous casting (Figure 7).

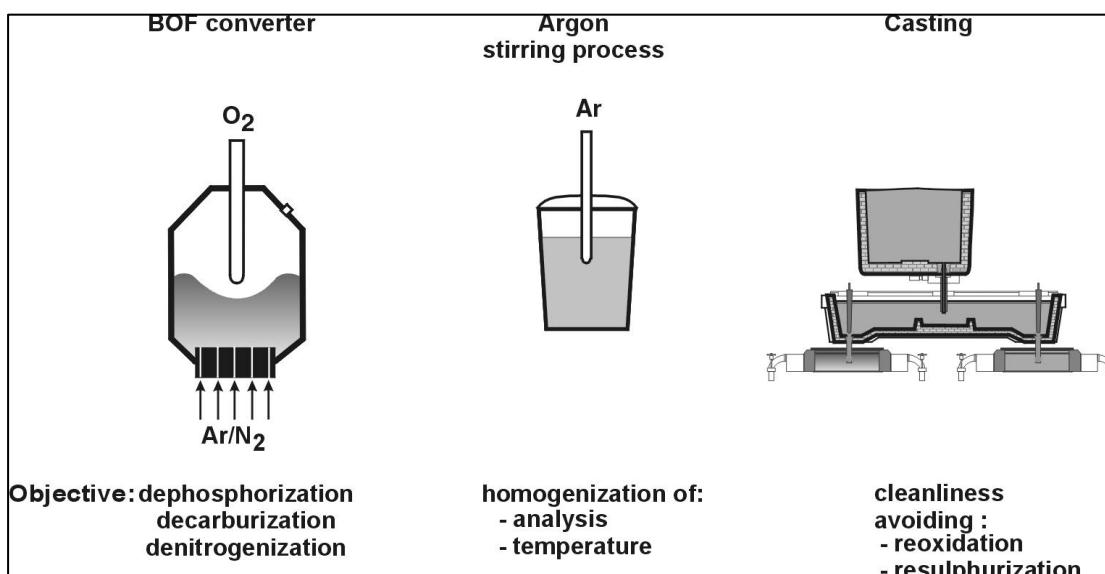
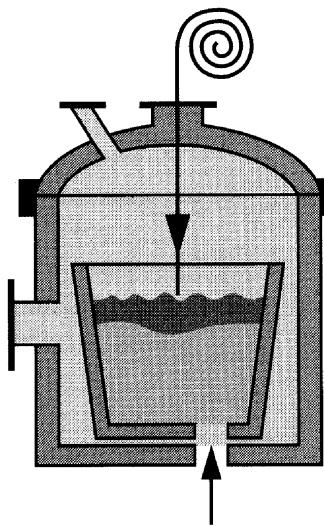


Figure 7: Basic process stages for steel production on BOF route.

A bubbling process was conducted in the ladle for the purpose of homogenization of composition and temperature. As noted initially, secondary metallurgy, in particular, has contributed to a significant improvement in steelmaking productivity and quality. What, then, are the tasks and objectives of secondary metallurgy (1) (Figure 8). The first aim, at tapping of the steel from the LD converter or the electric furnace into the ladle, is phase separation of steel

and slag, i.e., the achievement of slag-free tapping. A further objective is the deoxidation of the crude steel and adjustment of alloying element contents to achieve with the specified target analysis. The casting temperature for the downstream casting process must be adjusted precisely during secondary metallurgy. A further task of secondary metallurgy is the improvement of cleanliness. Here, cleanliness can be interpreted as both oxide and sulphide purity. Calcium treatment makes it possible to perform systematic inclusion modification. Vacuum treatment is performed to lower the amount of the gases hydrogen and nitrogen dissolved in the steel. It is possible during vacuum treatment of a non-deoxidized steel to adjust carbon contents to ultra-low levels. An additional function of secondary metallurgy is frequently that of performing desulphurization of the steel. Finally, homogenization of the heat's composition and temperature must always be assured throughout the secondary metallurgical process. These examples are intended to illustrate how diverse the tasks of secondary metallurgy may be. The various treatments may be performed individually or in combination, depending on the particular grade of steel and/or its intended use.

- Separation of steel and slag phases during tapping and casting
- Deoxidation of raw steel
- Adjustment of alloying contents according to the target analysis
- Adjustment of the casting temperature
- Improvement of the steel cleanliness
- Inclusion modification
- Removal of the dissolved hydrogen and nitrogen contents in the steel
- Decarburization
- Desulphurization
- Homogenization of the steel



Stahl und Eisen 118 (1998) Nr. 1

Figure 8: Tasks and objectives of the secondary metallurgy.

The trend in the achievable contents for a number of selected elements is shown in the following (Figure 9) (2). The introduction of vacuum decarburization made it possible to achieve a significant lowering of carbon contents. Carbon contents of 20 ppm can nowadays be achieved. Demands for 10 ppm are anticipated for certain applications. In the case of phosphorus contents, 100 ppm is now achievable with no special treatments. Demands for phosphorus contents down to 30 ppm are anticipated in the future for specific applications. The introduction of hot-metal and steel desulphurization means that sulphur contents of 10 ppm can now be reliably achieved. No demands for even lower sulphur contents are expected. A figure of 30 ppm is now achievable for nitrogen content. Contents of 20 ppm will be required in the future for steels for a number of applications. 15 ppm is now achievable for total oxygen content. The lowest contents required in the future will probably be around 10 ppm. Vacuum treatment made it possible to reduce hydrogen contents to around 1 ppm. These low contents

will remain adequate for the foreseeable future. It can be stated by way of summary that it will be necessary to achieve even lower figures in the next few years for the elements carbon, phosphorus, nitrogen and oxygen, and that these demands will again constitute a challenge to the steel-maker.

Content \ Year	1960	1980	2000	Future
Carbon	250	150	20	10
Phosphor	300	150	100 (50)	30
Sulphur	300	30	10	10
Nitrogen	150	70	30	20
Total Oxygen	30	30	15	10
Hydrogen	6	6	1	1
Total amount	1036	436	176 (126)	81

Figure 9: Achievable contents in ppm.

A number of stages during the steelmaking process and their influence on the reduction of the respective contents are shown below for the elements carbon, phosphorus, sulphur and total oxygen (Figures 10a and 10b).

In the case of carbon, the introduction of converter bottom bubbling achieved an initial reduction for the LD process. A further significant reduction occurred as a result of the introduction of vacuum treatment. Yet another reduction in carbon contents was achieved in the form of process-engineering improvements to vacuum treatment, and the increase in the suction capacity of the ejectors used. The introduction of converter bottom bubbling also produced an initial reduction of phosphorus for the LD converter process. The introduction of slag hold-back systems for converter tapping achieved a further reduction in phosphorus contents. The introduction of heating during secondary metallurgy made it possible to lower converter tapping temperature, producing a further reduction in phosphorus contents. Subsequent heating of the steel in the ladle is necessary in this case. A dual-slag process in the converter now permits the reduction of phosphorus contents to 50 ppm. Both the introduction of hot-metal desulphurization and of steel desulphurization produced significant reduction of Sulphur content. The combination of these two processes means that sulphur contents of 10 ppm can now be reliably achieved. Shrouded casting was initially necessary to achieve ultra-low total oxygen contents. A further improvement was then achieved with the combination of cleanliness bubbling and calcium treatment.

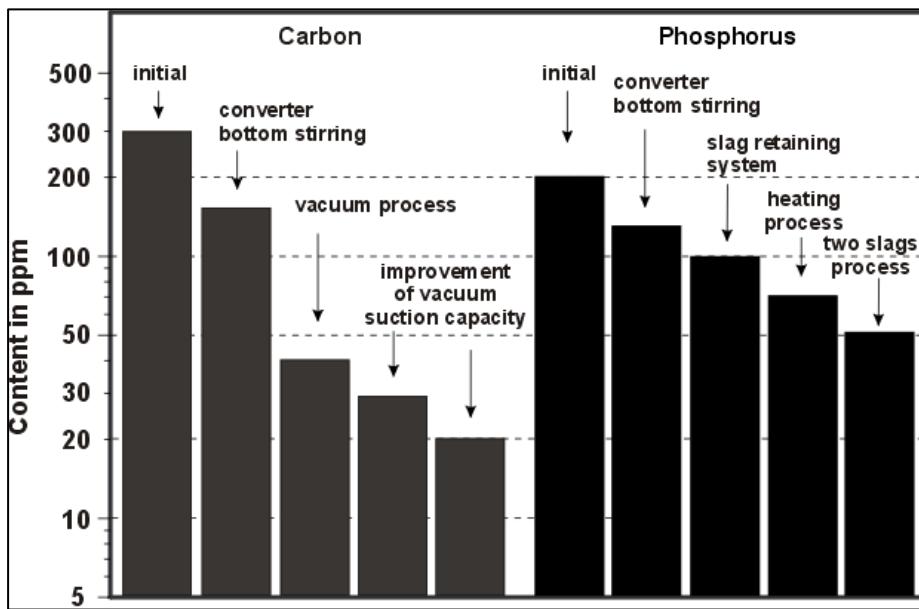


Figure 10a: Course of possible C and P contents due to process improvement.

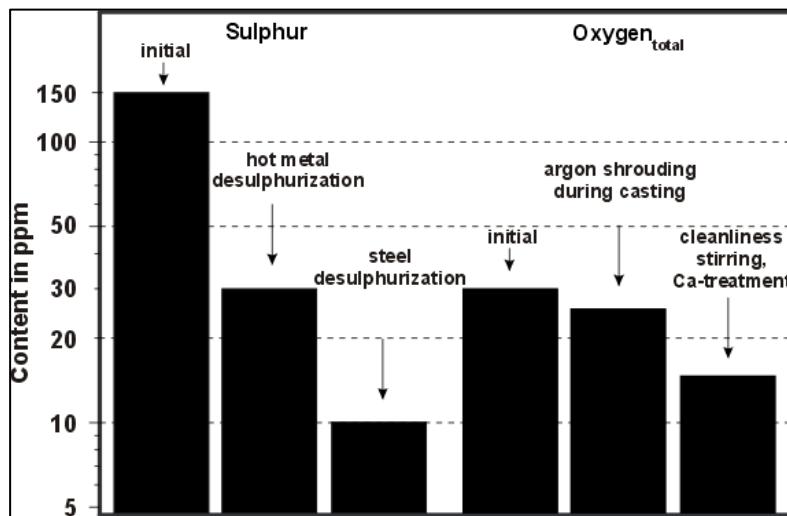


Figure 10b: Course of possible S and O_{tot} content due to process improvement.

The steelmaking process route is nowadays quite variable, depending on the steelplant's production range (Figure 11). It generally starts with hot-metal desulphurization, subsequent oxygen top blowing process in the converter, followed by secondary metallurgy, with argon bubbling in the ladle, and vacuum treatment (in the form of RH treatment or treatment in a ladle tank degassing installation). Heating of the steel may follow if necessary. This heating is possible either in a ladle furnace or by means of an aluminothermic heating process. Inclusion modification by means of treatment with calcium-containing materials occurs at the end of secondary metallurgy. The steel is then cast using the continuous-casting process.

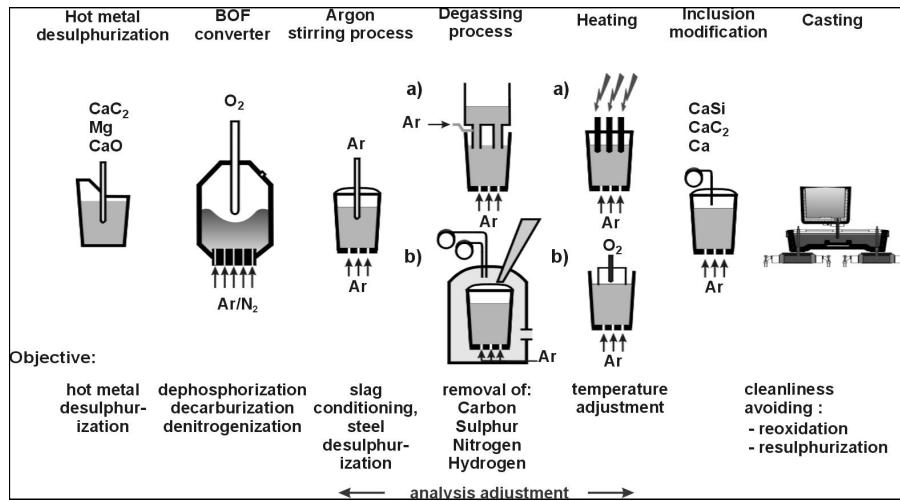


Figure 11: Possible process stages for steel production on a state of the art BOF route.

Adjustment of Low Phosphorus Contents

Let us now examine in detail the provisions nowadays practiced for the reduction of specific elements, and the provisions and processes which can be derived from them for the future. We shall take phosphorus as the first element (Figure 12). Phosphorus contents of between 40 and 100 ppm can nowadays be achieved in a single-stage converter process, depending on the silicon and phosphorus content of the hot metal. The hot metal silicon content is determined by the quantity of slag, in which the P₂O₅ formed during dephosphorization is fixed. Hot metal dephosphorization with subsequent low-slag blowing in the converter is nowadays propagated, from Japan, in particular. Discussion of it shows that phosphorus of 40 ppm can be achieved using this two-stage dephosphorization at the end of the converter process. It must be noted in this context, however, that hot-metal dephosphorization is preceded by silicon removal, with the result that the converter process can be operated with extremely low silicon contents. The advantage here can be found in the low quantity of converter slag. This process, on the other hand, does not permit high levels of scrap charging. A two-stage converter process, in which the slag is either removed in the converter after the first blow or the steel is tapped unkillled into a steel ladle and charged back into the converter again for another blow, makes it possible to attain phosphorus contents of 30 ppm at the end of the converter process. All the phosphorus contents shown here are contents at the end of the converter process. These values may rise again if small amounts of converter slag, from which the P₂O₅ is then reduced, are carried over at tapping. The addition of alloying elements, and of ferromanganese with low phosphorus contents, in particular, also causes a slight rise in phosphorus contents, with the result that the phosphorus contents achievable in the finished product are around 10 ppm higher than the phosphorus contents at the end of the converter process. It is apparent from this that the selection of appropriate processing stages certainly permits the achievement of low phosphorus contents in the 30 to 40 ppm range. Phosphorus contents of below 100 ppm can be achieved easily without any special provisions in the single-stage converter process.

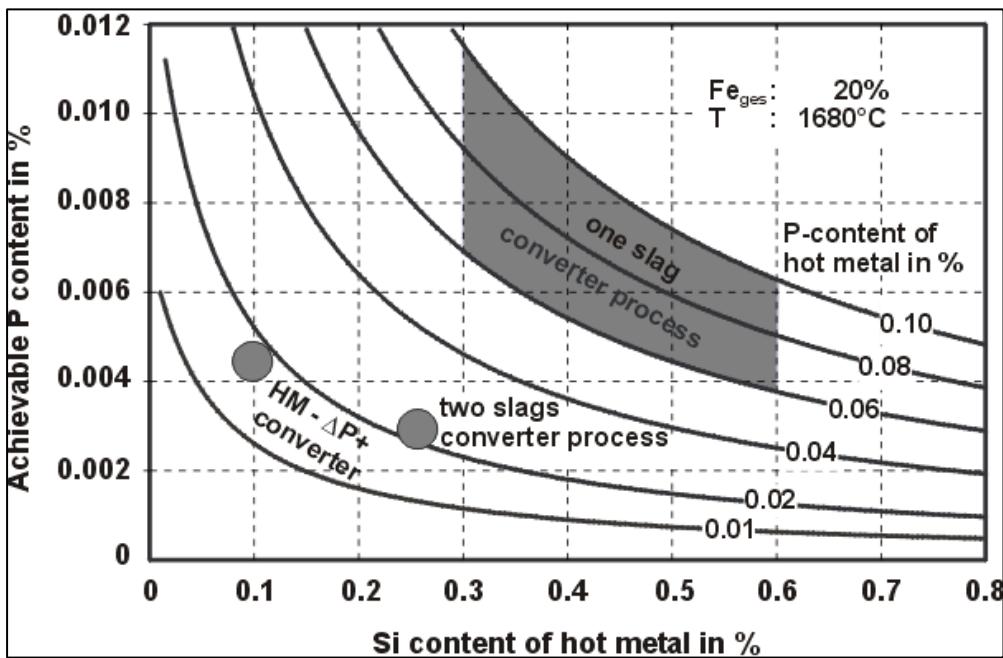


Figure 12: Achievable P content depending on process route.

As a result of the increasing use of ladle furnaces and alternative heating methods, in particular, it became possible to use a different process route in secondary metallurgy for the attainment of low phosphorus contents (Figure 13). This route consists of lowering converter tapping temperature by around 50 °C. The phosphorus contents achievable for an iron content in the converter slag of 15 % and a P_2O_5 content of 1.8 % are shown for a tapping temperature of 1700 °C. This produces equilibrium phosphorus contents of around 130 ppm. The lowering of tapping temperature to 1650 °C results in equilibrium phosphorus contents of slightly above 80 ppm. This means that a decrease in tapping temperature of 50 °C achieves phosphorus contents almost 50 ppm lower. It is necessary to balance out this lower tapping temperature by means of subsequent heating of the steel during secondary metallurgy. By way of comparison, the figure also shows phosphorus equilibrium values for the second process stage in a two-stage converter process. Converter slag iron content is around 18 %, P_2O_5 content is some 0.4 %. Phosphorus contents in the converter of 20 ppm can thus be achieved at tapping temperatures of 1700 °C. This again indicates that various processing routes can be taken, depending on the target phosphorus contents. Achievable phosphorus contents are between 20 and 130 ppm.

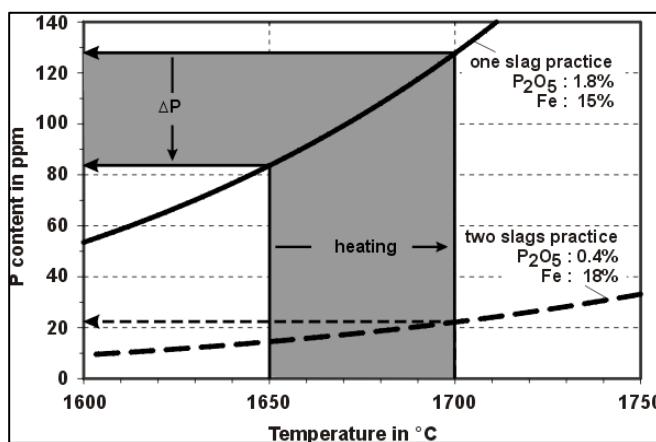


Figure 13: Achievable P content vs. temperature and P_2O_5 content.

Adjustment of Low Sulphur Contents

Desulphurization during the BOF steel production process takes place in the three stages of hot-metal desulphurization, desulphurization in the converter, and steel desulphurization. Desulphurization in the electric furnace and steel desulphurization are, of course, possible in electric-furnace steelplants. The target for attainment of ultra-low sulphur contents must be that of achieving a cost-optimized combination of the various process stages, since the reduction of sulphur content in the hot metal is possible only to a limited extent. Hot-metal desulphurization by means of injection of calcium-carbide magnesium or lime-magnesium mixtures permits the achievement of sulphur contents of down to 20 ppm in the hot metal, depending on the quantity of desulphurization agent injected. Desulphurization in the converter or the electric arc furnace is negligible, with the result that steel desulphurization then remains as the final stage (Figure 14).

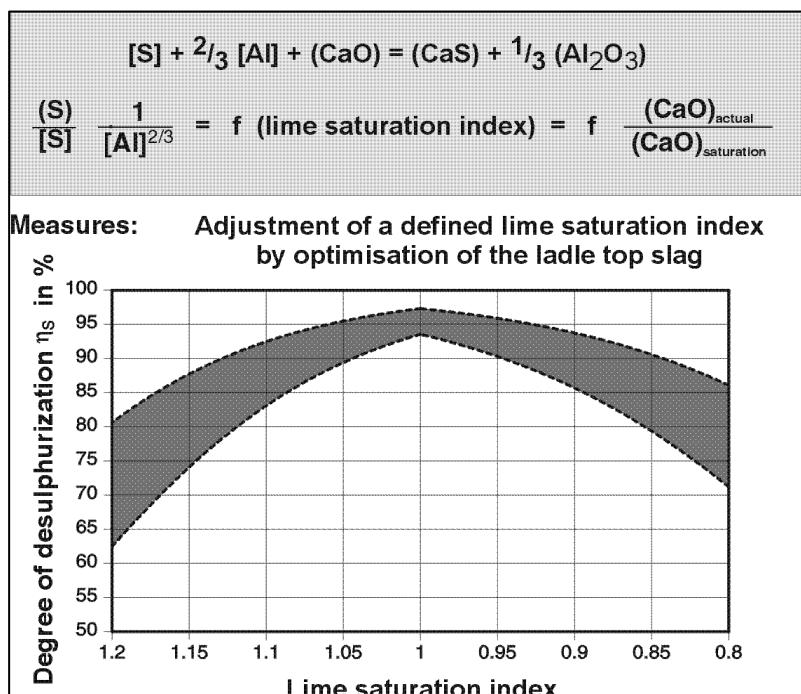


Figure 14: Achievable degree of desulphurization ($Al = 0.03\%$ and $15\text{ kg slag/t steel}$) as function of lime saturation index.

The following provisions are necessary for the achievement of good desulphurization efficiency (3, 4, 5): A surplus of aluminium must be provided. The ladle slag must be lime-saturated, and intensive bubbling-treatment of the heat in the ladle is necessary in order to ensure high desulphurization kinetics. A so-called "degree of lime-saturation" has been defined to characterize the ladle top slag. The degree of lime saturation identifies the position of the current ladle top slag referred to lime saturation. A degree of lime saturation of 1 signifies that the ladle top slag is lime saturated. A degree of lime saturation lower than 1 indicates a lime-subsaturated homogeneous liquid slag. A degree of lime-saturation of more than 1 signifies a lime-supersaturated heterogeneous slag. Operating tests for degree of desulphurization as a function of degree of lime saturation have been performed during steel desulphurization. A 95 % degree of desulphurization can be achieved under a lime-saturated ladle top slag. Desulphurization efficiency falls in the case of lime-subsaturated slags. This can be attributed to a decrease in the CaO activity of the ladle top slag. Desulphurization efficiency also drops

in the case of supersaturated slags. The reason for this can be found in the poorer kinetics of steel desulphurization under the heterogeneous slag.

Reactions other than steel desulphurization also occur during intensive bubbling of the heat in the ladle (6). These are, on the one hand, slag reduction of the SiO_2 from the ladle top slag with the aluminium, with the formation of Al_2O_3 , and an increase in silicon contents. Reoxidation of the aluminium with air oxygen also occurs simultaneously. Figure 15 shows the decrease of sulphur and aluminium contents with time when these diverse reactions are taken into account. A slight aluminium burn-off occurs for pure desulphurization. Aluminium consumption rises during the bubbling process as a result of the slag reduction which occurs simultaneously, and an additional aluminium burn-off occurs again when a reoxidation of the heat is also additionally taken into account. As a result of slag reduction, the manganese content of the heat rises slightly, since the MnO in the ladle top slag is reduced. A significant rise in silicon contents occurs, however, as a result of the reduction of the SiO_2 from the ladle top slag. This increase in silicon contents is undesirable, particularly for the production of low-silicon steels, for sheet and strip grades, for instance. It can be suppressed by lowering the intensity of the bubbling process, which then naturally results in a deterioration of desulphurization efficiency.

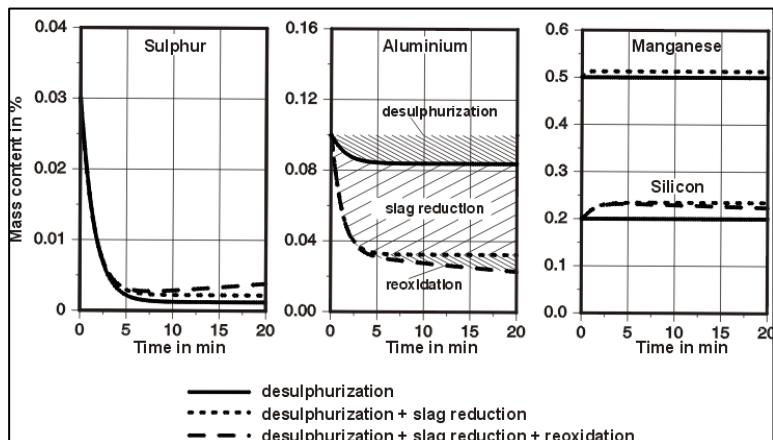


Figure 15: Influence of reaction-type on changes in steel composition.

As already illustrated, a desulphurization efficiency of 92 % can be achieved with certainty under optimum conditions. Desulphurization efficiency falls to 75 % as a result of a reduction of stirring intensity. Desulphurization efficiencies of 35 % can be achieved with only short stirring of the heat and low bubbling gas delivery rates. Figure 16 shows the sulphur contents necessary in the hot metal and the target contents at the end of the converter process as a function of achievable desulphurization efficiency during secondary metallurgy and target sulphur content at the end of secondary metallurgy.

Under optimum desulphurization conditions, hot-metal desulphurization is then necessary only for the achievement of maximum sulphur contents of 10 or 20 ppm. Desulphurization of the steel alone is entirely adequate for higher sulphur contents. Hot-metal desulphurization is generally always necessary for a desulphurization efficiency of 75 %. Hot-metal desulphurization down to 30 ppm must be performed, for example, to achieve a maximum ultimate sulphur content of 20 ppm in this case. Intensive hot-metal desulphurization must also be performed in the case of relatively low desulphurization efficiencies during secondary metallurgy of, for example, 35 %. Desulphurization of the hot metal down to around 30 ppm is necessary in this case to achieve a maximum ultimate sulphur content of, for example, 50 ppm.

Hot-metal desulphurization down to 150 ppm is necessary for the attainment of a maximum ultimate sulphur content of 100 ppm.

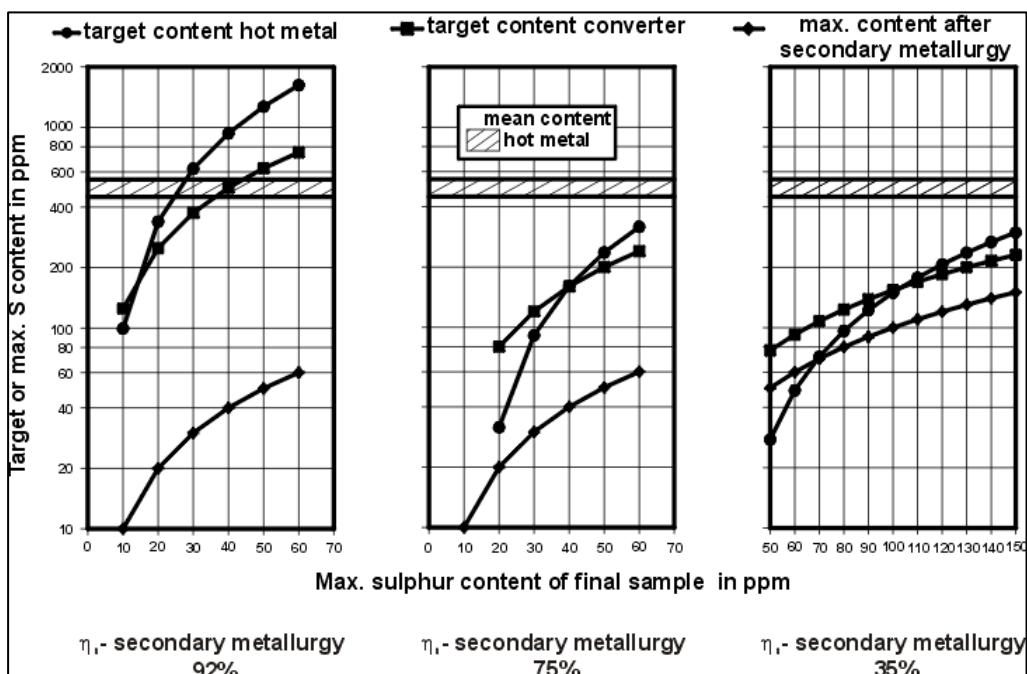


Figure 16: Development of sulphur content during the steel making process.

Inclusion Modification

Inclusion modification is accomplished by means of the addition of calcium-containing materials, such as CaSi, for example (7). The CaSi can either injected via a lance, or added to the heat in the form of cored wire. Inclusion modification should be studied within the CaO-Al₂O₃-CaS ternary system (Figure 17). Starting from the remaining Al₂O₃ deoxidation products, the inclusions are modified from Al₂O₃ to CaO as a result of the addition of calcium. It is important that the supply of calcium is such that complete conversion of the oxides to liquid calcium aluminates occurs. If sulphur contents are high, the formation of CaS inclusions also occurs in addition to the conversion of the Al₂O₃ deoxidation products to liquid calcium aluminates. In this context, it is important to avoid precipitation of CaS as function of sulphur content and to shift the deoxidation products into the liquid calcium aluminates range. In the case of elevated sulphur contents, in particular, this is no longer possible, since formation of CaS occurs primarily prior to the conversion of the alumina to liquid calcium aluminates. These circumstances are shown again in Figure 18.

The modification of the deoxidation products from Al₂O₃ into the liquid calcium aluminates range as a function of calcium addition is apparent. The formation of solid calcium sulphides begins as from a certain amount of added calcium, depending on sulphur content, however. The range in which liquid calcium aluminates are formed before the precipitation of solid calcium sulphides occurs is the liquid inclusion range. The aim must be to hit this "window of liquid inclusions" accurately during secondary metallurgy. It is clear from the figure that this window is relatively large, given sufficiently low sulphur contents of 20 ppm. At sulphur contents of 500 ppm, for example, precipitation of solid calcium sulphides occurs before the

liquid calcium aluminates are formed. Effective oxide modification is therefore not possible at such high sulphur contents, since the calcium is consumed for the formation of the calcium sulphide.

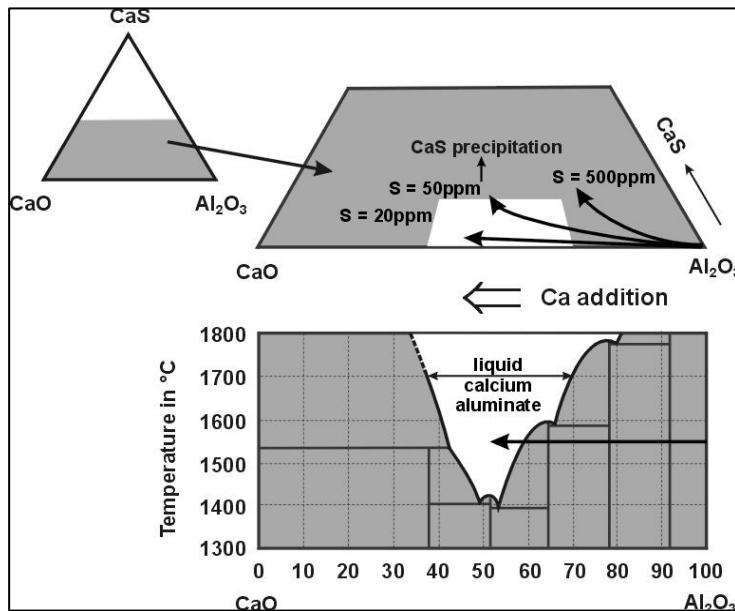


Figure 17: Inclusion modification during calcium treatment.

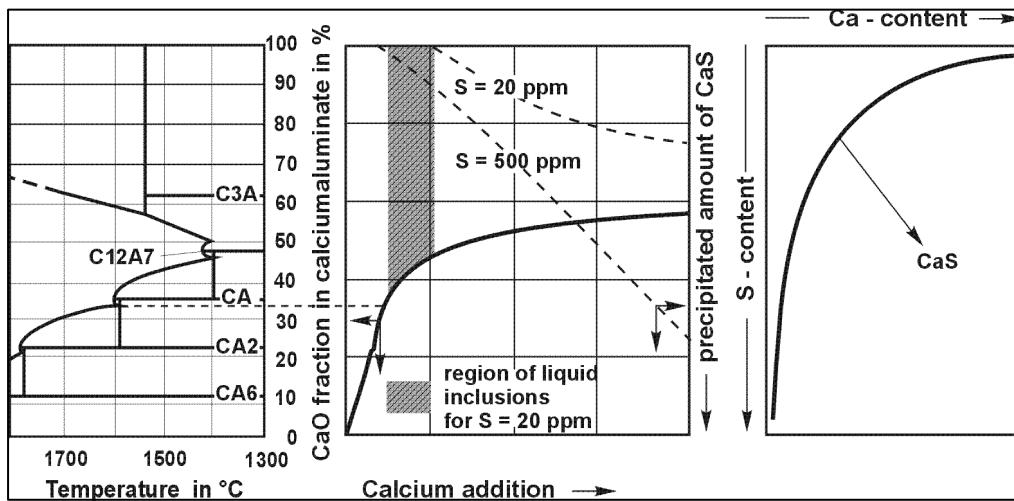


Figure 18: Formation of oxides and precipitation of CaS during calcium treatment.

Adjustment of Low Nitrogen Contents

The next element which we shall examine is nitrogen. Nitrogen contents of 20 ppm can be achieved at the end of the converter process, depending on the converter bottom-bubbling gas used, i.e., nitrogen or argon. Higher nitrogen contents are found in electric furnaces. Nitrogen pick-up of a greater or lesser magnitude occurs at tapping of the steel from the converter or electric arc furnace into the ladle, depending on the precise time of addition of the first

deoxidation element (Figure 19). Tapping with no nitrogen pick-up is possible only with unkilled tapping, in which subsequent deoxidation is performed only in the ladle (8).

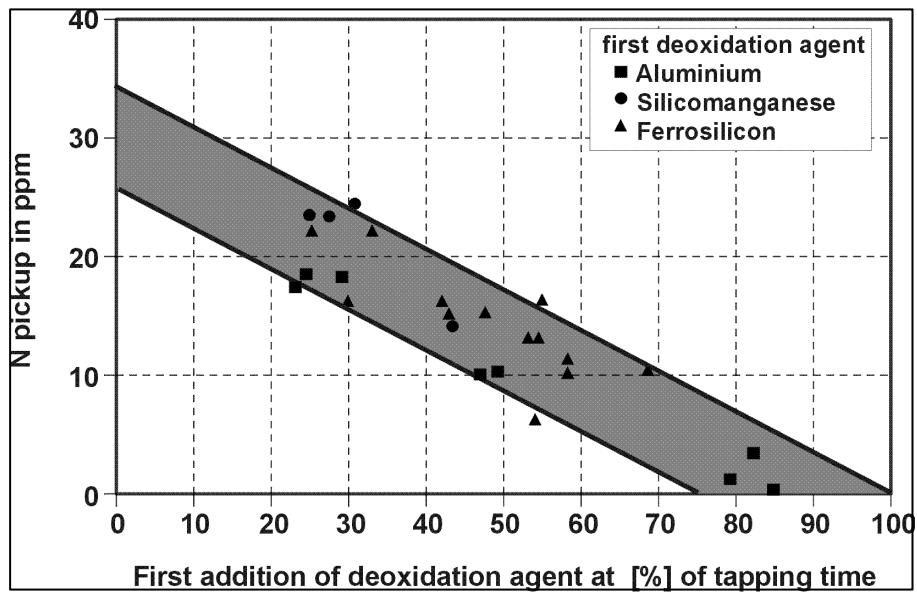


Figure 19: Nitrogen pickup during tapping from BOF into the ladle.

Removal of nitrogen from the heat during vacuum treatment is possible in principle. Since nitrogen, like sulphur and oxygen, is a surface active element, ultra-low sulphur and oxygen contents are the precondition for a significant decrease in nitrogen contents during vacuum treatment. Figure 20 shows the plot of nitrogen contents as a function of bubbling-gas throughput during vacuum treatment in a ladle tank degassing unit for a sulphur content of 10 ppm and dissolved oxygen content of 2 ppm. Nitrogen contents of 30 ppm can be achieved at the end of vacuum treatment for a nitrogen content of 50 ppm prior to vacuum treatment. At higher initial nitrogen contents of 90 ppm, nitrogen contents of 40 ppm are achieved at the end of vacuum treatment under otherwise identical conditions. This means that significant removal of nitrogen occurs during vacuum treatment, particularly in the case of elevated initial nitrogen contents, provided sulphur and oxygen contents are sufficiently low. The lower initial nitrogen content, the less pronounced the removal of nitrogen during vacuum treatment.

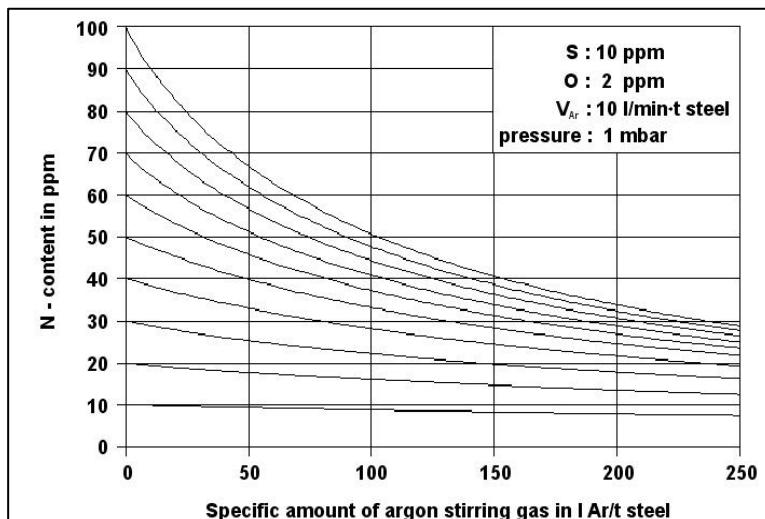


Figure 20: Evolution of nitrogen during vacuum treatment.

The influence of the surface active element sulphur is shown again in Figure 21.

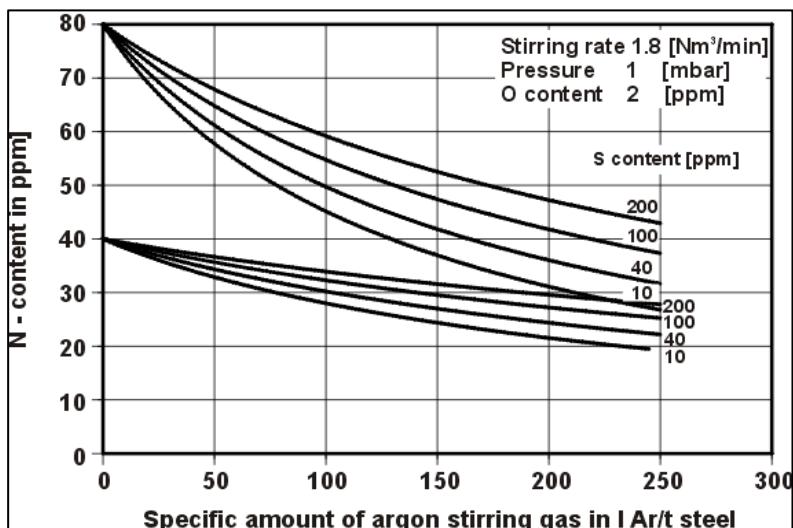


Figure 21: Influence of sulphur on the decrease of nitrogen during vacuum.

Starting from initial nitrogen contents of 40 and 80 ppm respectively, the figure shows the nitrogen contents achievable at the end of vacuum treatment as a function of the specific argon bubbling-gas throughput. The influence of sulphur content is clear, i.e., ultra-low sulphur contents are a basic precondition for the assurance of optimum conditions for effective nitrogen removal during vacuum treatment. The result of denitrogenation is poorer if sulphur contents rise during vacuum treatment.

Adjustment of Low Carbon Contents

Vacuum decarburization for achievement of ultra-low carbon contents is nowadays standard practice. The process is generally performed either in an RH system or in a ladle tank degassing facility with a non-deoxidized steel. The dissolved oxygen is thus able to react with carbon, forming CO. Carbon pick-up into the steel, from the ladle lining, for example, can occur during vacuum treatment, or from the casting flux powder, during casting. Figure 22 shows the improvements implemented for the achievement of low carbon contents in vacuum decarburization in a ladle tank degassing facility (9). It has become possible thanks to optimization of analytical systems, to improve the average to around 36 ppm, starting from an average of some 38 ppm in the finished sample. The use of low-carbon casting powders produced a further improvement down to an average of around 31 ppm. A significant enhancement was achieved via the selection of a different ladle lining. The first tests were performed in a ladle with a dolomite lining and with magnesite in the slag zone. Both the dolomite and the magnesite had carbon contents of 5 to 8%. The use of a bauxitic ladle lining with magnesite in the slag zone made it possible to lower the average achievable carbon content down to 20 ppm. These results demonstrate the influence of ladle lining on achievable carbon contents. Ultra-low carbon contents following vacuum treatment and up to the casting process can be achieved only via the use of carbon-free ladle lining materials.

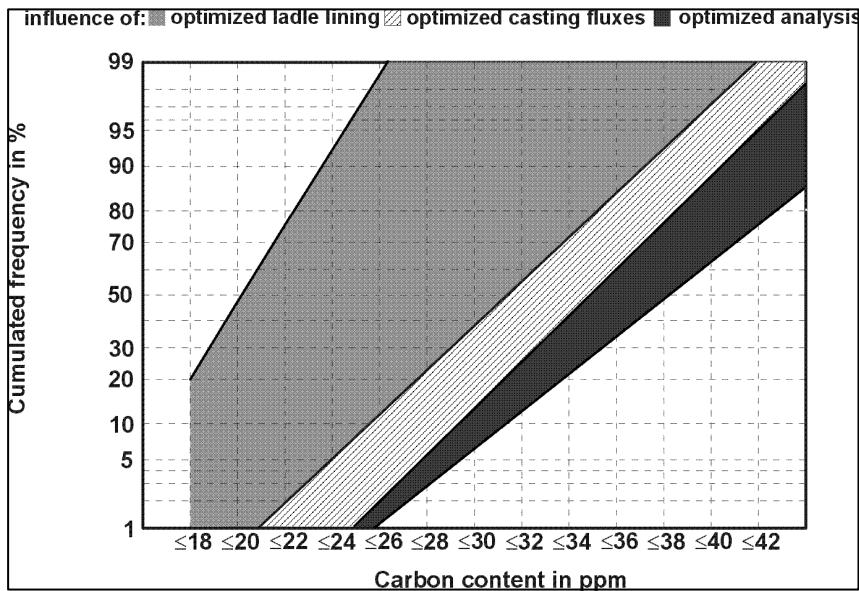


Figure 22: The effects of various parameters on achievable carbon contents.

Decarburization and desulphurization of the steel during secondary metallurgy are two competing and contradictory reactions. Desulphurization of steel requires a fully deoxidized heat. For vacuum decarburization, on the other hand, the heat must not have been deoxidized. Four working ranges can be read off in Figure 23, depending on the sulphur content and carbon content specifications for a range of grades. The manner of operation for the production of various grades of steel is outlined below. Only hot-metal desulphurization is necessary for the production of the 100Cr6 ball-bearing steel. Hot-metal desulphurization and steel desulphurization must be performed for production of plate and strip grades. The production of interstitial free (IF) deep-drawing grades necessitates both hot-metal desulphurization and decarburization of a non-deoxidized steel. Hot-metal desulphurization is performed for production of dynamo steels, followed during secondary metallurgy first by vacuum decarburization and, after deoxidation of the steel heat, moderate steel desulphurization. This discussion illustrates that precise coordination of hot-metal desulphurization in combination with subsequent secondary metallurgy, i.e., vacuum decarburization and/or steel desulphurization must be implemented as a function of the target sulphur and carbon contents in the grade to be produced.

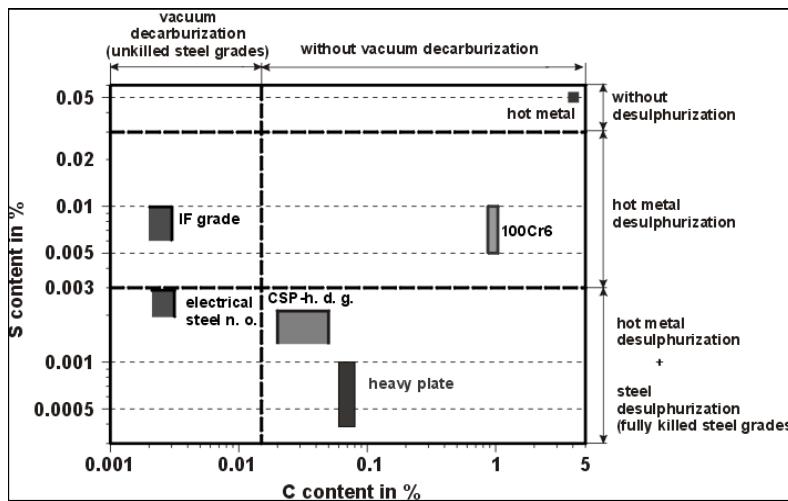


Figure 23: Process stages to achieve S and C contents for selected steel grades.

Adjustment of Oxide Cleanliness

So-called "cleanliness bubbling" is performed at the end of secondary metallurgy for the attainment of high oxide purity. The term "cleanliness bubbling" signifies in this context the bubbling of small flows of rinsing gas through the heat under a closed ladle top slag. Cleanliness bubbling promotes the expulsion of the remaining oxides into the ladle top slag (Figure 24).

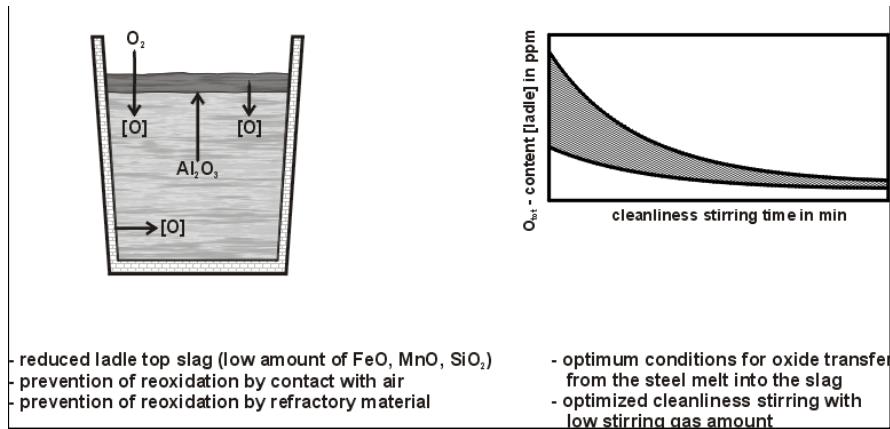


Figure 24: Conditions for the adjustment of high oxide cleanliness in the ladle.

A number of basic preconditions are necessary for the achievement of optimum cleanliness bubbling and, therefore, of high oxide purity. First, the ladle top slag must have been completely reduced. "Completely reduced ladle top slag" signifies that the FeO , MnO , and SiO_2 contents must be as low as possible. On the other hand, reoxidation of the heat as a result of contact with the air must be avoided. Reoxidation of the heat from the refractory material of the ladle lining must also be excluded. In addition, optimum conditions must be provided for expulsion of the oxides out of the heat and into the ladle top slag.

This oxide elimination mechanism in the ladle top slag is assisted by bubbling using extremely low flows of rinsing gas. Figure 25 shows the decrease in total oxygen contents as a function of cleanliness bubbling time. Total oxygen contents of lower than 20 ppm can be achieved easily after a bubbling time of 10 to 15 minutes.

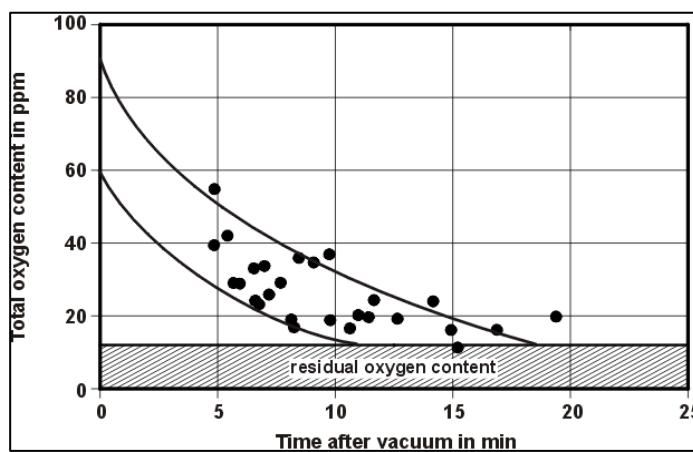


Figure 25: Total oxygen content as a function of time during cleanliness stirring.

The final decrease in total oxygen contents occurs during the continuous-casting process. The remaining oxides can, on the one hand, be eliminated in the tundish or, on the other hand, during strand-casting. Figure 26 shows the results of model computations for oxide elimination

during the continuous-casting process as a function of caster type (10). As is apparent, the lowest amount of oxygen removal occurs on the oval-bow caster. Elimination improves upon transition to a bow-type caster or a vertical bending caster. The best results are obtained in casting of the steel on a fully vertical caster. Since the construction of a vertical continuous caster is in many cases not possible, or a bow-type is already installed, account is taken of these facts with the installation of a vertical section of some 2.5 to 3 m in length on the bow-type caster.

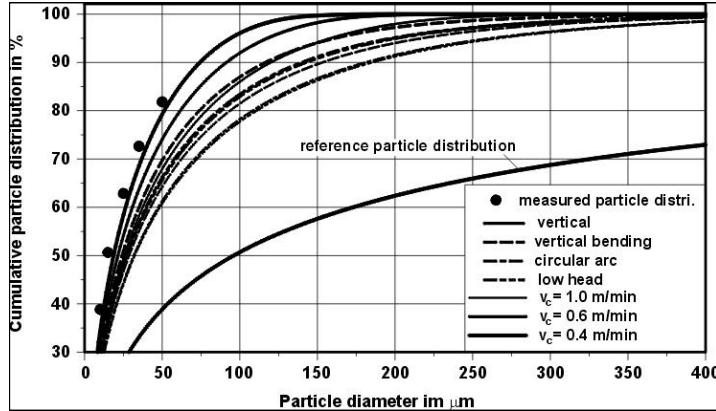


Figure 26: Particle distribution expected in slabs on the various types of casters.

Figure 27 shows the improvement in macroscopic cleanliness following conversion of a bow-type caster with a curved mould to a vertical-bending caster with a vertical section of 2.5 m. The improvement in oxide purity achieved with this modification is clear.

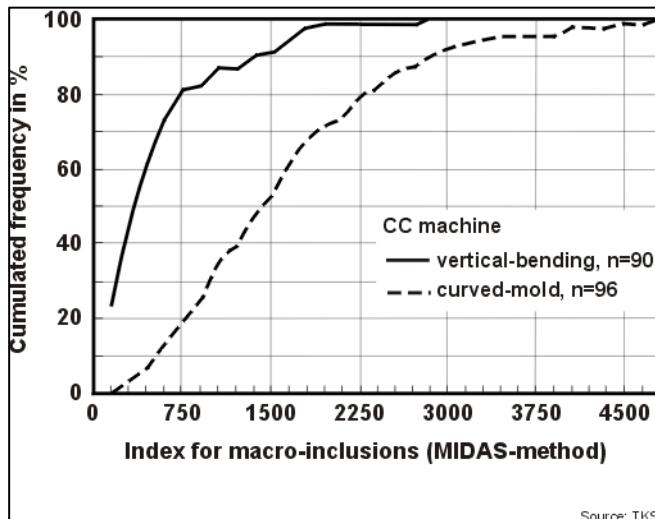


Figure 27: Cleanliness of slabs cast by circular arc and vertical bending machines.

Figure 28 shows the oxygen distribution across slab thickness for a vertical caster and for a bow-type caster. In the case of the vertical caster, the inclusions are able to rise up to the casting powder in the mould throughout the solidification period. In contrast to this, on a bow-type caster, the inclusions are trapped by the solidified strand shell at a certain bending radius and are no longer able to ascend up to the mould. Greatly varying oxygen distributions across slab thickness are the corresponding result. On a vertical caster, homogeneous distribution of oxygen across the entire thickness of the slab is achieved. On a bow-type caster an accumulation of oxygen contents occurs in a highly defined inclusion band. This is the result of the trapping of the inclusions in the solidified strand shell mentioned above. It can easily be

imagined that such a heterogeneous oxygen distribution across slab thickness will also result in heterogeneous mechanical and technological properties in the end product.

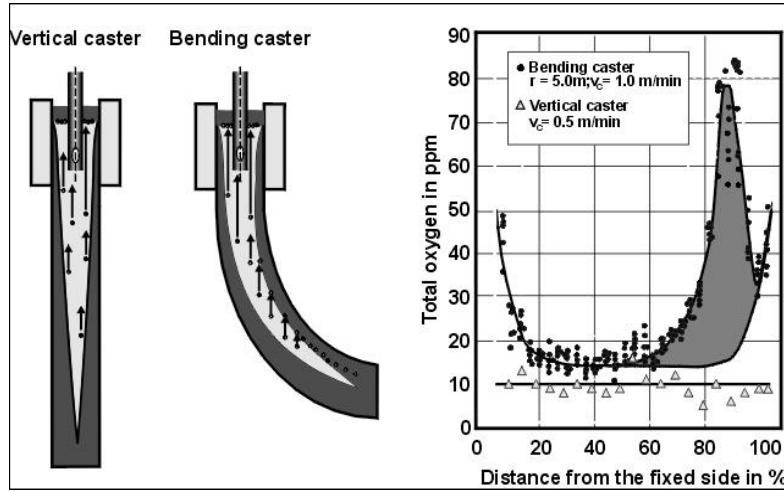


Figure 28: Distribution of oxygen over the slab thickness for different continuous casters.

Adjustment of Narrow Analysis Ranges

During tapping of the steel into the ladle and throughout the secondary metallurgy, composition is continuously checked by means of sampling and fine correction of steel analysis is made by the addition of the required alloying elements if necessary. The melting and mixing of the alloying elements added in the heat is dependent on various parameters (11). Melting time is determined by the melting temperature of the alloying element added and the current temperature of the steel. Stirring of the heat for mixing and homogenization of the alloying elements added is accomplished either by ladle-bottom rinsing bricks or by means of a bubbling lance. Figure 29 shows the change in manganese concentration as a function of the stirring process following the addition of ferromanganese.

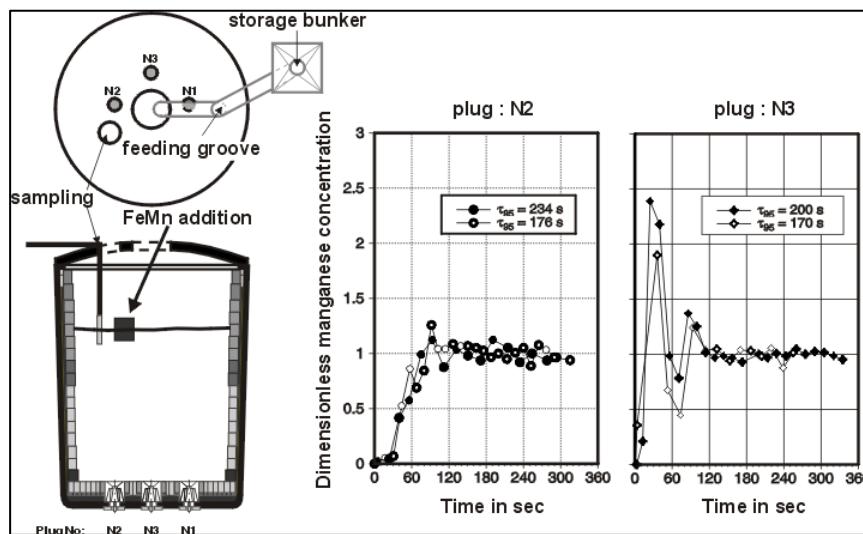


Figure 29: Schematic description of experimental apparatus and changes in melt composition after additions of manganese (stirring rate 200 l Ar/min).

It is clear that exponential approximation of manganese concentration to the final concentration occurs with stirring using plug No. 2 for the configuration stated for site of ferromanganese input, sampling and rinsing brick location. In contrast to this, the plot for manganese concentration is completely different for the use of plug No. 3. In this case, manganese concentration first overshoots, while the subsequent plot is similar to an attenuated oscillation, with gradually decreasing fluctuation around the ultimate manganese content. In both cases, ultimate manganese content is reached approximately 120 seconds after the addition of manganese and complete homogenization of the heat is assured.

In the case of fine correction of composition and the adjustment of tight composition fluctuations, in particular, corresponding demands are made on the efficiency of chemical laboratory. A so-called "capability index" is defined in order to delineate the potentials for achievement of specific composition tolerances. A certain analysis tolerance is specified for the various elements on the basis of the order (Figure 30).

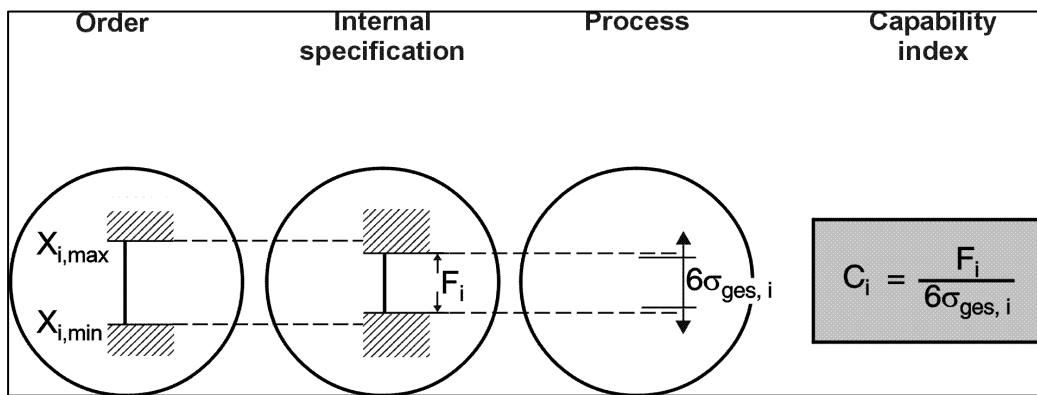


Figure 30: Definition of a capability index.

This analysis tolerance is generally narrowed down again by internal specifications. The steelmaking process produces a certain scatter in adjustment of the analysis tolerance. This scatter is the result of process scatter in the steelmaking process, the scatter from sampling and, in particular, analytical scatter. The capability index is the ratio of the specified analysis tolerance to six-fold the process scatter. Figure 31 shows, on the one hand, laboratory scatter for the various elements, i.e., the laboratory's measuring accuracy, and the narrowest analysis tolerances nowadays demanded, on the other hand.

The resultant capability index for the adjustment of narrow analysis tolerances for the various elements is also shown. It is thus apparent that laboratory scatter is still too high to permit the attainment of the narrowest analysis tolerances demanded, particularly in the cases of the elements manganese and carbon. In the future, it will be necessary to further decrease laboratory scatter for these two elements. In the case of niobium, analysis tolerances of 50 ppm can be achieved easily.

Element	$\sigma_{\text{lab.}}$	$6 \cdot \sigma_{\text{lab.}}$	most narrow range of analysis F	$C_p = \frac{F}{6 \sigma_{\text{lab.}}}$
Mn	0.0120	0.0720	0.05	0.70
C	0.0020	0.0120	0.01	0.83
V	0.0015	0.0090	0.009	1.00
Nb	0.0007	0.0042	0.005	1.19
Al	0.0020	0.0120	0.015	1.25
Si	0.0050	0.0300	0.05	1.66
Ni	0.0045	0.0270	0.05	1.85
Cu	0.0035	0.0210	0.05	2.38
Mo	0.0020	0.0120	0.03	2.50
Cr	0.0040	0.0240	0.10	4.16

Figure 31: Capability index of steel plant laboratories for different elements.

Surface Crack Free Casting

The aim during subsequent casting of the steel is that of maintaining the high metallurgical results achieved during secondary metallurgy. This signifies that carbon pick-up into the heat must not occur during the casting process, particularly in the case of ultra-low decarburized grades. Nor may sulphur pick-up of the heat occur; the high oxide cleanliness must be maintained. In addition, a product free of surface defects must be produced during continuous casting. Particular attention must be devoted in this context to the avoidance of surface cracking. The formation of transverse cracks on the solidified product is characterized by the toughness of the material in the immediate sub-surface zone. Figure 32 shows the reduction of area at fracture as a function of temperature for a steel containing 0.19 % carbon, 0.4 % silicon and 1.45 % manganese both without niobium, and with 0.03% niobium.

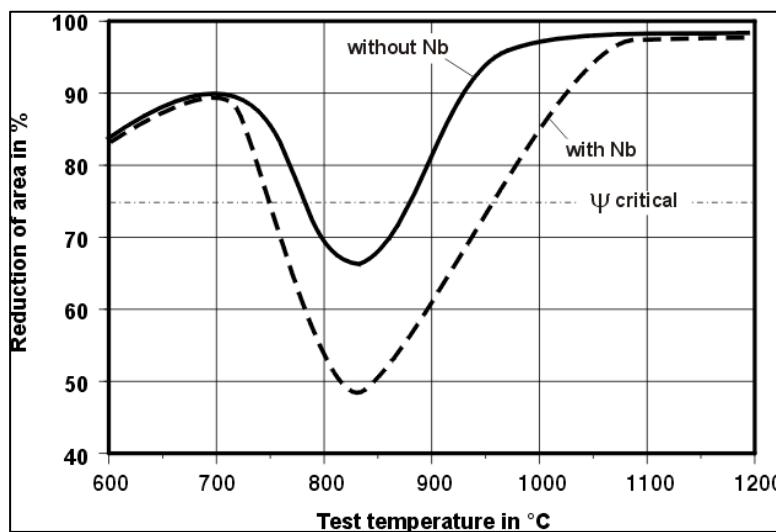


Figure 32: Effect of niobium on hot ductility.

In the niobium-free steel, toughness is reduced as temperature drops when temperature falls below 950 °C, i.e., a decrease in reduction of area occurs. The minimum reduction is located at a temperature of around 840 °C. The reduction of Area rises again as temperature drops further. In contrast to this, reduction of area at fracture drops in the same steel containing niobium as soon as temperature falls below around 1050 °C. This steel also has its minimum reduction of area at fracture at a temperature of around 830 °C, the minimum being located at a significantly lower level than in the case of the niobium-free steel. Reduction of area at fracture also increases again when temperature falls below 830 °C in the steel alloyed with niobium. If a reduction of area at fracture of above 75 %, that must be achieved during the casting process, is defined, it becomes apparent that this critical range occurs only within an extremely small temperature interval in the case of the niobium-free steel. The steel containing niobium, however, has a much larger temperature interval with a reduction of area below 75%. Transverse cracking occurs upon exposure to mechanical loads of the strand surface in a temperature range with low reduction of area. This means that the niobium-containing steel should only be exposed to mechanical loads at temperatures either above 950 °C or below 750 °C. In contrast to this, the critical temperature interval for the niobium-free steel is between 870 °C and 780 °C. This indicates that precise monitoring and control of surface temperature during the continuous-casting process is necessary, particularly for niobium-containing grades.

Figure 33 shows again in schematic form the dependency on temperature of reduction of area at fracture and surface temperatures along the length of the caster for two different cooling strategies (12).

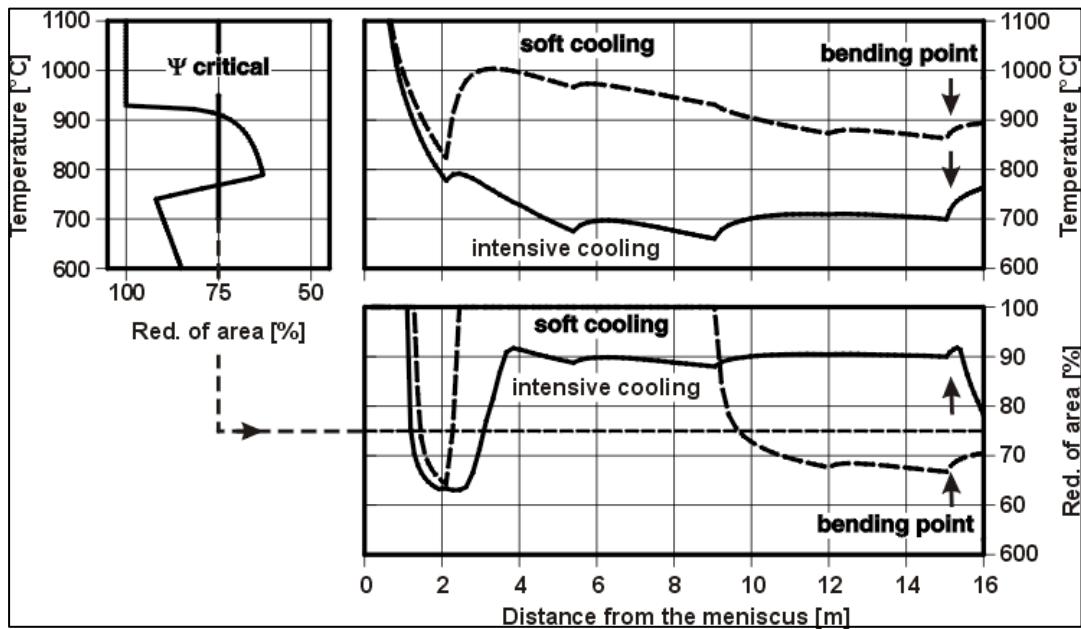


Figure 33: Influence of soft and intensive cooling on ductility.

In one case, surface temperature is lowered to temperatures below the critical temperature extremely quickly by means of intensive cooling, and also remains at this level until bending of the solidified strand occurs. The “soft cooling“ strategy attempts to achieve a temperature above critical along the entire length of the strand by means of only slight application of secondary cooling water. The lower figure shows the resultant reduction of area at fracture along strand length. In both cases, reduction of area at fracture falls below the critical reduction around 2m below the meniscus. From a point around 3m below the meniscus, the temperature

in both cooling strategies is in a range within which reduction of area at fracture does not fall below the critical 75%. In the soft-cooling strategy, however, so much heat is removed that surface temperature drops into the critical range from around 10 m of solidified strand length and the reduction of area at fracture falls below the critical level. In this case, transverse cracks on the slab surface must be expected as a result of the subsequent bending process at around 15 m. In the case of intensive cooling, the temperature at the bending point is also so low that reduction of area at fracture does not drop below the critical point.

Steel Plant Logistics

Only metallurgical requirements made on the steel plant process have been discussed up to now. There are, in addition to these, also other requirements, particularly with respect to steel plant logistics (Figure 34). The individual orders for steel are first assembled into continuous-casting sequences. A time-model for the steel plant process, in which the various process times for the individual treatment stages are specified, is derived from the continuous-casting sequences to be cast. Scrap and hot-metal supply models can be added on the raw-materials side. In addition, the availability of the various alloying elements must be planned, depending on the various grades to be cast. The time-model, for its part, provides the basis for a temperature model in which all target temperatures from the temperature at tapping from the converter or electric furnace up to and including the target temperature in the tundish are specified. Tundish and ladle availability planning also derive from the up-to-date casting programme. Systematic planning of repairs to the continuous casters can be implemented as a function of utilization of the individual casters. This example is intended to illustrate just how complex and diverse are the logistics of a steel plant and the way in which the individual planning models must be tailored to and coordinated with each other.

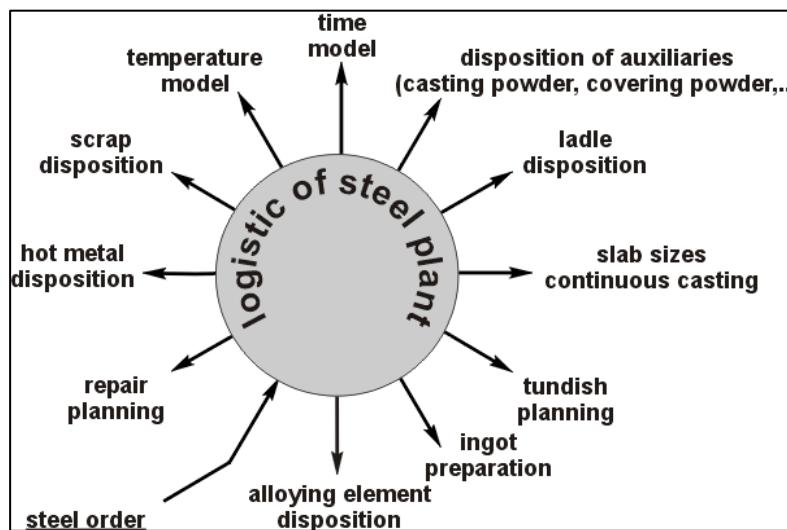


Figure 34: Logistic of steel plant.

Finally, Figure 35 shows, by way of summary, the various requirements made on the steelmaking process. It is necessary to fulfill the metallurgical demands discussed in detail above. In addition, it is also necessary to assure optimum conditions for processing. Product quality must also be assured, and the entire steel plant process must be overseen and monitored by a quality assurance system. It is necessary to satisfy all these requirements during the

steelmaking process to ensure repeatable steel plant production and therefore equally repeatable results in the semi-finished product.

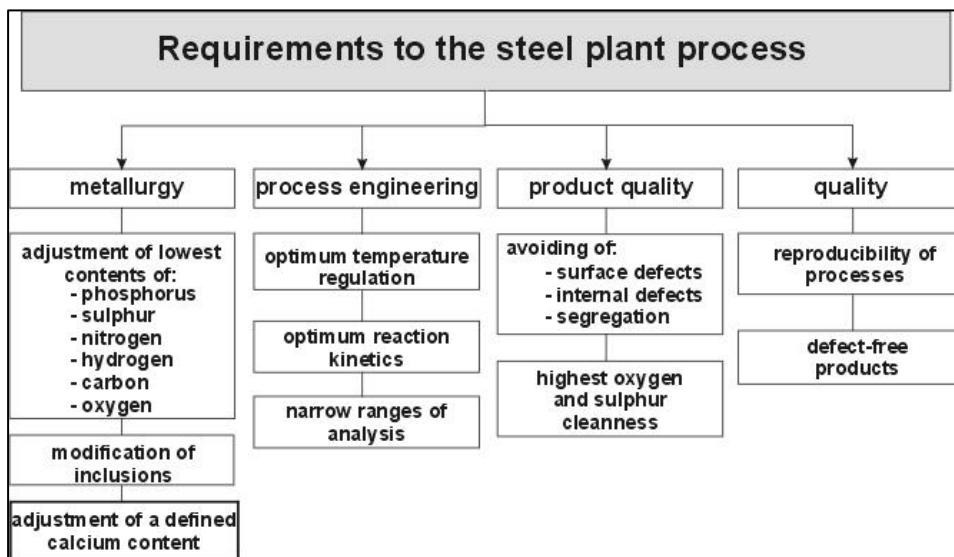


Figure 35: Requirements to the steel plant process.

References

- (1) Jürgen Cappel, Hans-Jürgen Ehrenberg, and Heinz-Peter Kaiser, *Stahl und Eisen*, 118 (7) (1998), 41-47.
- (2) Norbert Bannenberg, *Berg-und Hüttenmännische Monatshefte*, 142 (11) (1997), 467-472.
- (3) Bernd Bergmann, and Norbert Bannenberg, *Stahl und Eisen*, 111 (1) (1991), 125-131.
- (4) Norbert Bannenberg, Bernd Bergmann, and Henry Gaye, *Steel research*, 63 (10) (1992), 431-437.
- (5) Norbert Bannenberg, and Helmut Lachmund, *Steel Technology International*, (1994/1995), 103-107.
- (6) Norbert Bannenberg, Helmut Lachmund, and Bernd Prothmann, *Proceedings 77th Steelmaking Conference*, (Chicago, 1994), 135-143.
- (7) Norbert Bannenberg, *Proceedings 78th Steelmaking Conference*, (Nashville TN, 1995), 457-463.
- (8) Norbert Bannenberg, and Bernd Bergmann, *Stahl und Eisen*, 112 (2) (1992), 57-64.
- (9) Helmut Lachmund, *Proceedings 84th Steelmaking Conference*, (Baltimore, 2001), 613-623.
- (10) Klaus Harste, Norbert Bannenberg, and Karl-Hermann Tacke, *Preprints 9th Japan-Germany Seminar on Fundamentals of Iron and Steelmaking*, (Düsseldorf, 1996), 67-73.

- (11) N. Bannenberg et al., Stahl und Eisen, 119 (2) (1999), 37-44.
- (12) Norbert Bannenberg, Klaus Harste, and Jörg Klingbeil, Proceedings 2nd European Continuous Casting Conference, Vol. 1, (Düsseldorf, 1994), 187-195.