Journal of Chemical Technology and Metallurgy, 52, 2, 2017, 159-167

RECENT ACHIEVEMENTS IN IRON AND STEEL TECHNOLOGY

Lauri Holappa

Aalto University School of Chemical Technology
Department of Materials Science and Engineering
PO Box 16200; Espoo FI-00076
Finland
E-mail: lauri.holappa@aalto.fi

Received 15 September 2016
Accepted 16 December 2016

ABSTRACT

The basic technologies for modern iron and steel production were developed about half a century ago. Then and thereafter, raw materials pretreatments, coke making and blast furnace process itself were strongly improved, energy consumption and emissions were decreased as well as productivity and product quality were raised. Modern top, bottom and combined blowing converter processes were developed, which revolutionized steel production based on iron ore concentrates. Today, oxygen converter process is the main primary steelmaking technology with a share of about two thirds of the world steel production. Another mainstream of steelmaking is based on recycled steel as raw material. Smaller share of the scrap is used in converters as cooling material, but most of it is melted in ultra-high power electric furnaces. The progresses in these primary steelmaking technologies have been solidly associated with the emergence and developments of secondary steelmaking processes in ladles as well as with the breakthrough of continuous casting since 1960s. These technologies radically changed the whole steelmaking principle, which has meant much higher production rates, and lower materials and energy consumption per unit as well as unequalled premises for development of new steel grades with highly improved and strictly specific, tailored properties. The present paper discusses the latest achievements in different unit processes. Latest progresses in secondary metallurgy and continuous casting are considered with critical emphasis on the metallurgical constraints of the current processes. Finally, some future perspectives influencing the process development are discussed.

Keywords: *steelmaking, secondary metallurgy, continuous casting, process development.*

INTRODUCTION

The overall progress of steel production during the last 150 years is shown in Fig. 1 (scale on the right) and in Fig. 2 [1]. In the early 19th century, the world steel production was only some million tons annually. After the breakthrough of new processes, it exceeded 10 Mt in 1870 and 30 Mt in 1900. In 1927 the world production reached 100 Mt and 200 Mt in 1951. Then a “new industrial revolution” was undergone with innovative novel processes and extensive investments in new steel plants among others in Japan, Soviet Union, United States and South Korea. The steel production attained the level of 700 Mt/year in the 1970s (the record 749 Mt in 1979). Then the growth stagnated due to economic crises and political changes until the turn of the millennium, when it attained 850 Mt in 2000. That was the first sign of the recent “boom” in which China has been the major motor (Fig. 2). When China seemed to have reached a “saturation production level” other developing countries (India, Brazil and Russia in the forefront) have increased steel production remarkably. In the near future the growth in consumption will happen in developing countries.

At present, over 70 percent of crude steel is made by converter processes based on blast furnace hot metal. The rest is produced in electric furnaces utilizing recycled steel scrap as the iron source, with small share of direct reduced iron (DRI, Fig. 2). The open-hearth process which was important more than half a century has almost disappeared to 0.5 %. The current record production of crude steel 1,670 Mton was attained in the year 2014 [1].

OVERVIEW ON DEVELOPMENTS

Blast furnace ironmaking

Blast furnace process originates from the Middle Ages but was based on charcoal to the 18th century, when coke was learnt to make from "mineral coal" and to use in BFs [2]. Even in the beginning the sulfur problem and demands for optimal coke properties for BF were recognized. Enormous amount of work have been done during the three centuries to achieve the current level of technology. In early 1800, preheating of air blast came into operation. Since then the stove systems have strongly developed with enhanced heat efficiency, higher blast temperatures and pressure as well as air enrichment with oxygen. At the same time the furnace size has grown from early times "micro furnaces" to 4-5 m diameter "mini BFs" producing 100 kt/year in early 1900, to current 13-15 m diameter "mega" BFs producing 3-4 Mt/year. Another key factor in the development has been the improved iron raw material. Iron-rich ores/concentrates are used, agglomerated to sinter or pellets, designed charging for optimized, smooth burden descend and reduction process, melting and carburization. Due to rich iron burden quite small amount of slag is formed in current BFs. In old days, slag amounts might be over 500 kg/ton HM, then decreased to 300 - 200 kg/ton HM, today in some BFs only 150 kg slag/ton HM is formed.

Further merits in a modern BF can be found in process control. Sophisticated measuring devices to monitor the process state combined with advanced models are used to simulate, predict and control the operation.

A general benchmark of BF efficiency is its energy consumption. In 1950s typical coke consumption was 1000 kg/ton HM. Today the figure is typically from 500 to 450 kg/ton HM. Actually coke consumption can be much lower e.g. 300 kg/ton HM and the rest is coal powder which is injected via tuyéres with the hot blast. Powdered coal injection PCI is used for economic reasons to replace expensive coke whose amount is possible to decrease down to 250 kg/ton HM still maintaining the positive functions of coke layers, which are charged to control the even gas flow in the BF shaft [2].

Converter steelmaking

After development of coke blast furnace, the bottleneck in production rate was not in iron making but how to convert the carbon-rich "pig iron" into steel. Various oxidizing hearth treatments including puddling were inefficient. Only when Bessemer developed converter process based on air blowing through the vessel bottom in the 1850s, steel production could escalate as seen in Fig. 1. In the new process, the decarburization rate was more than an order of magnitude higher compared to any of the contemporary processes. The original Bessemer converter had acid silica lining which made it impossible to refine high-phosphorus hot metal which was

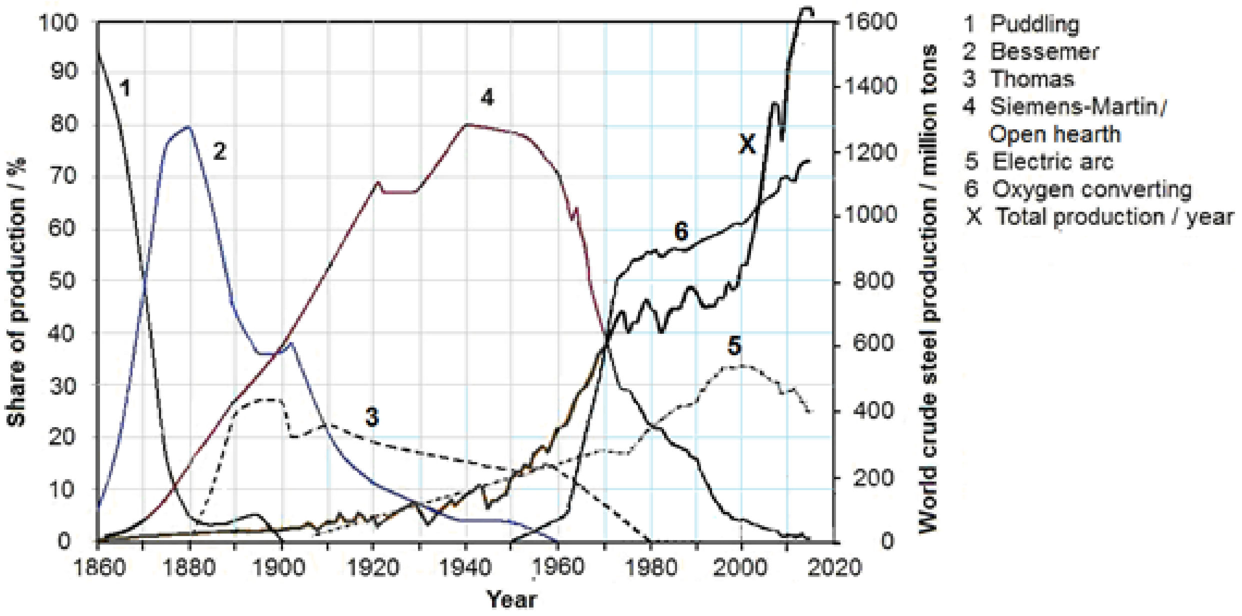

Fig. 1. Annual crude steel production since 1860 and share between various processes. Collected from archives in ref. [1].

common in British blast furnaces that time. The problem was solved when S.G. Thomas and P.C. Gilchrist succeeded to develop basic doloma lining and to apply it industrially in 1879 [3]. Hot metal could contain up to 2 % P. Then the "Thomas slag" formed as by-product had high P-content (around 5 wt %) and it was rich in lime (CaO) and thus an excellent fertilizer. Basic Thomas converters attained their share when high phosphorus iron ore was utilized.

In the 19th century, the role of oxygen in steel refining was well understood but there was no economic way to produce pure oxygen. Blowing air into steel resulted in high nitrogen content with harmful effects on steel quality. Large nitrogen volume had also a strong cooling effect thus lowering scrap melting capacity in Bessemer or Thomas converters. Use of oxygen instead of air was thus most desirable. After Bessemer´s era numerous attempts were done to use oxygen, however, catastrophic wear of the bottom or tuyère area was stated. In the 1920-30s, big scale production of oxygen gas was established making its use in process industry economically feasible. However, the problem of bottom wear still remained. The problem was surpassed by the invention of oxygen top blowing via a water-cooled supersonic lance. This technique was developed in the late 1940s and industrially introduced in Linz in 1952 [3]. The method is known as LD (Linz-Donawitz) or BOP (Basic Oxygen Process). LD process rapidly emerged in the 1960´s and displaced first the air-blown converter processes. For high phosphorus hot metal the old Thomas method was gradually replaced by a number of top-blown modifications. A rotary inclined converter with oxygen lance was developed by B. Kalling and installed in Domnarvet, Sweden in 1956 [3]. The process was called Kaldo. The movement of slag and metal resulted in intensive mass and heat transfer between the phases and efficient dephosphorisation was achieved. By using a secondary oxygen lance a remarkable part of the CO gas formed by carbon oxidation could be post combusted to CO_2. Exceptionally good heat economy was resulted, due to post-combustion, and up to 50 % scrap ratio could be reached [3]. A number of Kaldo converters were installed but when the raw material basis turned to low phosphorus concentrates the need for special converters gradually disappeared and the last Kaldos were closed towards the end of the 1970´s.

Also certain modifications of LD process with a special lance for combined oxygen - lime injection were developed for high-P hot metal in the late 1950´s i.e. LD-AC and OLP [4]. They survived until the 1980´s.

Oxygen bottom blowing was tried to solve at L´Air Liquid in Canada by G. Savard and R. Lee in the 1950´s among others with high pressure (over 2760 kPa) nozzles [5]. A final solution was, however, an annular nozzle in which oxygen was blown via the inner pipe whereas protecting/cooling gas e.g. propane was injected through the outer pipe. The first industrial bottom-blown oxygen converter was commissioned at Maxhütte, Germany in 1967 [5]. The process was named OBM (Oxygen-Bottom-Maxhütte). In the United States it was called Q-BOP. The share of bottom blown converters is around 10 % of the overall capacity of the converters. A similar principle of concentric nozzles was applied also in side-blown AOD converters for stainless steelmaking where inert argon gas is used as surrounding cooling gas but which at the same time dilutes CO gas formed from the decarburization reaction [6].

The experiences of the OBM process clearly revealed the principal drawback of the top blowing i.e. quite quiescent bath due to weak stirring effect of the oxygen jet. As a result, both the slag and the metal bath get over-oxidized. It was desirable to combine the benefits of the two processes to one process. Numerous combined processes were developed in the late 1970s to early 1980s, most of them were based on LD process with inert gas bottom blowing. These hybrid processes have today a great majority of the converters. The advantages of combined blowing compared with pure top blowing are:

- improved blowing efficiency owing to strongly intensified melt stirring;
- lower iron oxide in slag and better Fe yield;
- lower final oxygen content in steel and better yield of alloys and aluminum;
- increased refractory lining life by avoiding overheated, "FeO"-rich slag;
- increased hitting rate in composition and temperature due to better homogeneity;
- less splashing and spitting of slag.

Various converter technologies have been collected in Table 1 starting from original LD process, then LD-type processes with inert gas stirring, further O_2 top + O_2 bottom processes and pure bottom blowing process [7]. In addition, there are few allothermal combustion/

Table 1. Various Converter Technologies collected from the literature [7].

			Top blowing		Bottom blowing								
	Process	Developer	O_2	O_2 + fine CaO	O_2	O_2 + fine CaO	Gaseous hydro-carbons	Liquid hydro-carbons	N_2 +/or Ar	CO_2	Coke	Coal	Steam
Top blowing	LD	Voest-Alpine	+										
	LD-AC	Arbed-CRM	+	+									
	AOB	Irland Steel / Union Carbide	+	O_2 + Ar									
Top + bottom blowing I	LD-S	Voest-alpine	+						+				
	LD-KG	Kawasaki	+						+				
	LD-AB	Nippon-Kokan	+						+				
	LD-BC	CRM	+						+				
	TBM	Thyssen	+						+				
	M-TBI	Mannesmann	+						+				
	LBE	Arbed	+						+				
	NK-CB	Nippon-Kokan	+						+				
	LD-CL	Nippon-Kokan	+						+				
Top + bottom blowing II	LD-OTB	Kobe	+		(+)				+	+			
	LD-CB	Nippon-Kokan	+		+				+	+			
	LD-STB	Sumitomo	+		+				+	+			
Top + bottom blowing III	LD-OB	Nippon steel	+		+		+		+				
	LD-HC	Maxhütte	+	+	+		+		+				
	K-OBM	Klöckner	+		+		+	+	+				
	K-BOP	Kawasaki	+			+	+	+	+				
Bottom blowing	OBM/ Q-BOP	Maxhütte/ US-Steel			+	+	+	+	+				
	LWS	Creusot-Loire				+	+	+	+				
Allothermal processes	KMS	“			+	+	+	+			+	+	
	KS	“			+	+	+	+			+	+	
	Z-BOP	Zapsib	+								+	+	
High alloy steel converting	AOD	Union Carbide Lindé Division	+		+				+				
	VOD(C)	Witten (Thyssen)	+						+				
	CLU	Uddeholm/ Creusot Loire			+				+				+
	K-OBM-S	Maxhütte-Klöckner	+			+	+	+				+	

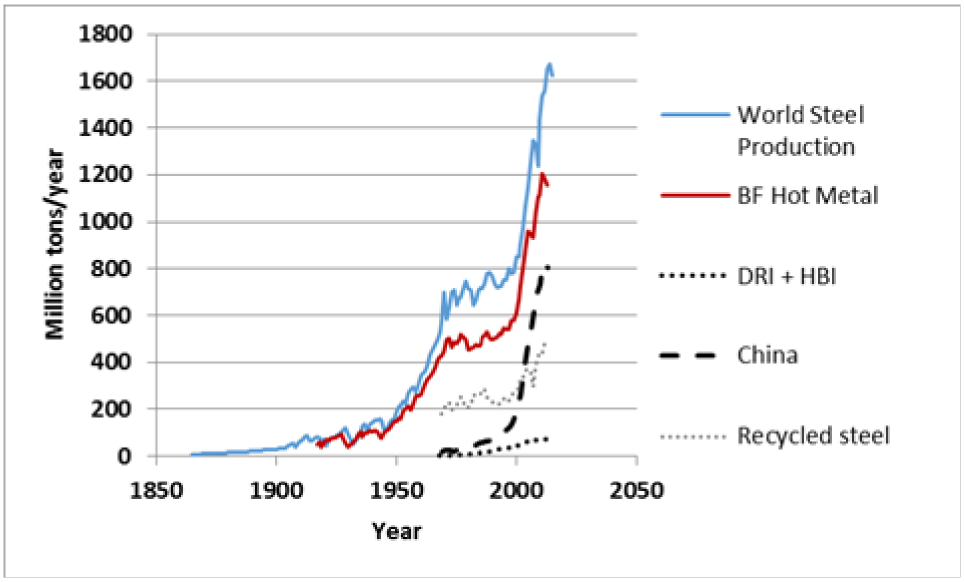

Fig. 2. World production of steel, blast furnace hot metal and direct reduced iron from 1860 to 2015. Also the steel production in China and the estimated fraction of recycled steel are shown [1].

heating processes for increased scrap melting and finally special converter technologies for stainless steel making.

Electric steelmaking

The application of electric arc furnace in steelmaking originates from 1889 by Paul Héroult [8]. Emerging started in the early 20th century when electricity generation spread widely. First furnaces had a capacity in between 1 to 15 t. The new technique suited well for scrap-based steel production. But EAF had a serious competitor namely Open Hearth (Siemens-Martin) process, which was also able to melt cold charge by combusting fuel. The niche of EAF was in special steels production, which required high temperature, flexibility for ferroalloys melting and long refining times. In the world statistics EAF outstripped Open Hearth until early 1980s.

In the 1960s, with the advent of continuous casting the EAF occupied another niche: it became the melting for mini-mills, feeding billet casters for the production of rebar and wire rod. The same idea has been adopted for strip production too.

Since 1960s the emergence of secondary metallurgy in ladles changed the whole philosophy of steelmaking. The process route divided into primary steelmaking in furnace (converter/EAF) and secondary steelmaking in ladles. Then the EAF reinvented itself as a melting-only unit. Another driving force was continuous casting which desired several heats in sequence. As the casting time per ladle was only one hour or less, which was a hard challenge for EAF. Ultra-high-power (UHP) furnaces were developed. Use of UHP led to fast furnace lining wear. This problem was solved by water-cooled panels in the upper walls and by adopting foaming slag practice. By these means, tap-to-tap times could match to casting times. Developments in EAF technology are listed in Fig. 3 [9]. As seen the tap-to-tap time has fallen down from 3 hours to 45 min. Electricity consumption has decreased from 630 to 350 kWh/t due to intensified melting, utilization of chemical energy i.e. oxy-fuel burners and scrap preheating. Even lower values, below 300 kWh/t has been reported. At the same time electrode consumption has come from 6.5 to 1.5 kg/t.

Ladle metallurgy

Primary steel making in converter is an oxidizing process in which the main aim is decarburization, and additionally phosphorus removal. In simple, conventional practice the crude steel was then tapped from converter into ladle and alloying performed in the tapping stream. Then the ladle was transported to casting yard. Different from converters, in open hearths and electric furnaces the charge could be heated which enabled further refining of the crude steel. The steel could be deoxidized, desulfurized and alloyed in the furnace. Initial oxidising slag was raked off and a new strongly basic “white” slag was formed [10]. Of course, such treatments were time-consuming, but then the "purified" steel was tapped into the ladle and transferred to casting. Thus ladle was only a transport container without any special treatment. Demanding steel grades were produced in electric furnaces or open hearths until 1970´s.

Then the steel making strategy has totally changed. Crude steel is made in the primary furnace (converter, EAF), then it is tapped into a ladle with typically main alloying made during tapping. Then the ladle treatments follow. They mean adjustment of the steel composition, refining or "cleaning" from harmful impurities and aiming at a target temperature for casting. For these purposes unit processes, deoxidation, desulfurisation and degassing via vacuum treatment are used. Gas rinsing or inductive stirring are methods for melt movement, promotion of steel/slag reactions, removal of deoxidation products and homogenization [10]. For heating and temperature control of the steel melt electric arc heating (ladle furnace) or chemical heating (like CAS-OB) are used. After the treatments in the ladle the steel has the required composition and cleanliness which must be maintained or even improved during the subsequent casting process. During casting the liquid steel must be prevented from reoxidation i.e. any contact with surrounding atmosphere must be avoided. In modern continuous casting process the steel is teemed from the ladle to a tundish and from the tundish to molds. All the streams must be shrouded by inert gas, protecting slag or air-tight construction.

The secondary refining processes thus consist of several unit processes, the most common of which are deoxidation, desulfurization, degassing (removal of hydrogen and eventually nitrogen) and decarburization to low or ultra low carbon contents. Naturally, the needs for different unit processes depend on the steel grade and its requirements. Additionally, alloying and composition adjustment as well as heating and control of temperature can be also regarded as unit processes.

Without going more deeply into secondary metallurgical processes and progresses during the recent decades, we can summarize the essential results. Concerning special steel grades with "extreme purity" requirements, the lowest attainable contents can be defined. These impurities are H, N, O, S, P and C. As discussed afore it depends on the steel grade which of these elements are critical. In IF steels (Interstitial Free) it is important to have low contents of hydrogen, nitrogen and carbon. In ULC (Ultra-Low-Carbon) grades the main object is carbon. A concrete way to describe the progress in secondary steelmaking e.g. during the last 50 years is to show how the achievable contents of impurities in steels have developed. In Table 2 the data were partly collected from literature and partly estimated by the author [10, 11]. Especially in estimating the future values towards the year 2020, we must keep in mind thermodynamic constraints to avoid simple linearization. Basic progresses in secondary metallurgical processes are presented at the Table bottom showing emerging of vacuum treatment, combination of vacuum with oxygen blowing, heating in ladles with arc (LF) or chemical heating by applying exothermic oxidation reaction of aluminum with oxygen. In 1960-70s hybrid methods including vacuum treatment and heating in the same unit were already erected. Nowadays separate units for vacuum treatment and heating are much more common.

"Cleanliness" is another property in modern steels, frequently debated, partly measurable in-line but gen-

Table 2. Progress of achievable contents of impurities in steel, ppm [10 -15].

Content **Year**	**1960**	**1985**	**2010**	**Future**
Total Oxygen	30	15	10 (6)	3-5
Carbon	250	50	15	10
Phosphorus	300	100	50	30
Sulphur	300	30	10	<10
Nitrogen	100	50	30	20
Hydrogen	6	3	1	<1
Process development	→ Vacuum: RH/DH/TD → VOD/RH-OB → OMVR* → Heating: LF/ ChemHeating → → → → { OMVR + → Hybrid (Asea-SKF)/Finkl/VAD → → { Heating			

* Optimized Mixing Vacuum Reactor

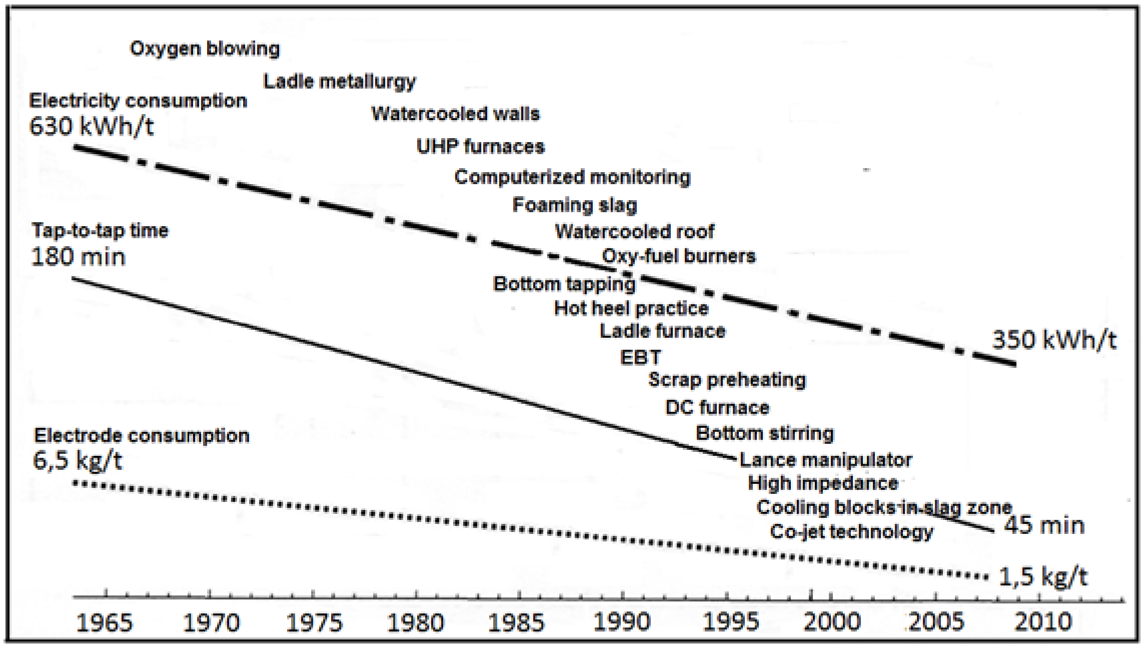

Fig. 3. Developments in EAF technology since 1965. Modified from [9].

erally needs more specific post-monitoring. Generally "clean" steel is connected to low amount of nonmetallic inclusions especially oxides, but can concern other inclusions, sulfides, nitrides, carbides or carbonitrides too. The criterion is not only the mass fraction of inclusions but their type, size, shape and distribution in steel. Finally, the physical properties of inclusions and their influence on steel properties define the cleanliness. There are several techniques to characterize inclusions in steel e.g. by optical and scanning electron microscopy, extraction technique and ultra sound testing which can be done for specimens taken by sampling liquid steel, solid ingot or rolled semi-product or final product.

The general progress of steel cleanliness as described in terms of total oxygen content is shown in Fig. 4 [10 - 15]. Until 1960s most demanding grades like ball bearing steels were produced in acid open hearth furnaces where deoxidation was based on Si and Mn as well as carbon resulting in Otot over 40 ppm. There were lot of inclusions but they were relatively harmless. When vacuum technologies and ladle furnaces became available, the Otot content was halved until 1980s. In order to strengthen deoxidizing power the practice was changed to aluminum deoxidation. Then the efforts were directed to efficient inclusions´ removal. A drawback came up due to low dissolved oxygen [O] and high [Al] in steel i.e. the threat of reoxidation during ladle treatments and casting via air and from oxidizing components in slag and refractory materials. The recent efforts have been aimed to eliminate these detrimental effects. In the next chapter this problem is further discussed.

Continuous casting

Continuous casting is the important linking process between steelmaking and rolling. As early as 1856, Henry Bessemer suggested a twin-roll caster but as industrial casters for steels generalized only since the 1960s [16]. In the mid-1980s, continuous casting exceeded the conventional ingot casting. It afforded lot of benefits compared to ingot casting: better yield, improved cast structure and homogeneity, and remarkable savings in energy and labor. Today, over 96 % of the world's steel production is cast by continuous casting including majority of steel grades and wide variety of dimensions. The casting and solidification phenomena are not discussed here, but the focus is on "clean casting".

In a modern caster the steel is teemed from the ladle to a tundish and from the tundish to molds. The role of tundish was originally to function as a "reservoir and distributor" for liquid steel from the ladle into the molds in a multi-strand caster. Recently, the potential of an "active tundish" was realized and its functions were extended to improved control of steel temperature and chemistry. As the steel cleanliness is an important issue

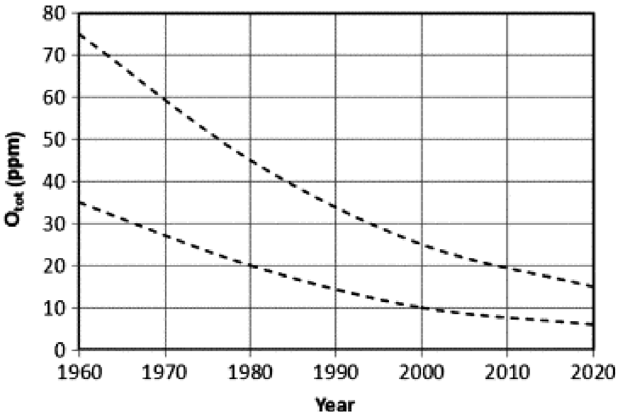

Fig. 4. Progress of total oxygen content in "high grade steels" since 1960. The figure is semi-schematic but based on data in the literature [10 - 15].

today, the role of tundish is considered both to promote inclusion removal from the liquid steel and to prevent appearance of new often macroscopic inclusions, which are most harmful for steel quality.

As the IISI Study on Clean Steel [15] and the book by Sahai and Emi on Tundish technology for clean steel production [12] showed, impressive developments on tundish design and operation have been done to promote inclusion removal and to protect steel melt from reoxidation. Shrouding systems between ladle and tundish and tundish and mold are used as well as covering slags in tundish and mold. An alternative method is a tundish filled with inert gas. However, the occurrence of exogenous macro inclusions in transient periods of casting practice (e.g. beginning of the casting sequence, ladle change, change of casting speed) has not yet been eliminated for difficult steel grades at a high throughput rate [12].

Since the tundish is the last reactor in which noticeable metallurgical operations can still be performed, the tundish covering slag plays an important role in controlling the quality of the cast product. If the steel interaction with the tundish slag could be optimized the steel quality could be maintained and improved in the tundish. An appropriate tundish slag should be capable to absorb deoxidation and reoxidation products. It should bind macro-inclusions occasionally entering from ladle [17].

FUTURE PERSPECTIVES

The world steel consumption is dependent on world economy and its future development. However, it is indisputable that certain growth will happen due to the progress in developing countries, their infrastructure, housing, transportation, etc. Conservative scenarios even forecast 50 % increase to 2050 meaning 2,500 Mton steel, annually. That is badly discordant with the goals to stop the *global warming* and to cut the CO_2 emissions. Energy saving and transfer from fossil energy to less-carbon and C-free energy forms by developing current processes and developing new ones are the main issues of steel industry today and in the future [18].

Steel is a central material for the mankind. It has, however, to compete and develop in order to keep its position. When aiming at better properties on cheaper price the limits of the processes come along. Modern computer technology, digitalization, process monitoring and advanced process control systems are useful tools in future production technology. However, "Big Data" cannot alone solve metallurgical problems, but the experts, who know the physico-chemical laws and constraints, are still needed. "Clean steel" is one such example which will surely be in the focus and in which the limits can be defined and even in practice approached.

CONCLUSIONS

Most of the current processes in iron and steelmaking date back to principles which developed in the mid of 20th century. Since those days, however, great advancements have been done.

In this review, the main achievements in blast furnace process, converter process and electric arc furnace steelmaking were surveyed. The role of ladle metallurgy and continuous casting in modern steelmaking were discussed with the main emphasis in "clean steel" production.

Finally, the future perspectives of the steel industry towards the year 2050 with targets for radical decrease of CO_2 emissions were considered.

Acknowledgements

The author is grateful to the Organizing Committee of ICMM'2016 and Professor Rossitza Paunova for the invitation and possibility to contribute this conference.

REFERENCES

1. http://www.worldsteel.org/statistics/statistics-archive.html
2. Y. Yang, K. Raipala, L. Holappa, Ironmaking: in S. Seetharaman, (Ed.), Treatise on Process Metallurgy,

Vol.3: Industrial Processes, Part 1 Ferrous Process Metallurgy; L. Holappa, (Ed.), 2-88, 2013.

3. R.F. Barracglough, Steelmaking 1850-1900, 320, The institute of Metals, London, 1990.
4. E.M. Michaelis, Basic oxygen steelmaking - a new technology emerges, Proceedings, The Metals Society, London, 1979, 1-10.
5. P.J. Mackey, J.K. Brimacombe, Solid-Liquid and Gas-l,iquid Interactions in a Bath-smelting Reactor. Proc. Savard/Lee International Symposium on Bath Smelting, The Met. Society of AIME, Warrendale, PA, 1992, 353-375.
6. W.A. Krivsky, The Linde argon-oxygen process for stainless steel; A case study of major innovation in a basic industry. Metall. Trans., 4, 1973, 1439-1447.
7. H. Jalkanen, L. Holappa, Converter Steelmaking; in S. Seetharaman, (Ed.), Treatise on Process Metallurgy, Vol.3: Industrial Processes, Part 1 Ferrous Process Metallurgy; L. Holappa, (Ed.), 2013, pp. 223-270.
8. H.M. Cobb (Ed.), Dictionary of Metals, Appendix I: Metals History Timeline, ASM International, Materials Park, OH, USA 2012, 304.
9. H.-B. Lüngen, M. Peters, P. Schmöle, Measures to increase efficiency and to reduce CO_2 emissions in iron and steelmaking in Germany and Europe. AISTech 2012 Proceedings, 109-119.
10. L. Holappa, Secondary Steelmaking; in S. Seetharaman, (Ed.), Treatise on Process Metallurgy, Vol.3: Industrial Processes, Part 1 Ferrous Process Metallurgy; L. Holappa, 2005, pp. 301-346.
11. L. Holappa; On Physico-Chemical and Technical Limits in Clean Steel production Steel research, 81, 10, 2010, 869-874.
12. Y. Sahai, T. Emi, Tundish Technology for Clean Steel Production, World Scientific Publishing Co. Singapore, 2008, p. 316.
13. L. Zhang, B. Thomas, State of the art in the control of inclusions during steel ingot casting, Met. Trans. 37B, 10, 2006, 733-761.
14. R. Fandrich, H.-B. Lüngen, C.-D. Wuppermann, Actual review on secondary metallurgy, Rev. Met. Paris, 105, 7-8, 2008, 364-374.
15. K. Wünnenberg, S. Millman, M. Nadif, C. Marique, M. Sumida, H.-J. Weddige, IISI Study on Clean Steel, IISI Techco 2004, p. 503.
16. S. Louhenkilpi, Continuous Casting; in S. Seetharaman, (Ed.), Treatise on Process Metallurgy, v. 3: Industrial Processes, Part 1 Ferrous Process Metallurgy; L. Holappa (Ed.), 373-434.
17. L. Holappa, M. Kekkonen, S. Louhenkilpi, R. Hagemann, C. Schroder, P. Scheller, Active Tundish Slag. Steel Research Int., 84, 2013, 638.
18. L. Holappa, Toward Low Carbon Metallurgy in Iron and Steel Making, Proceedings of the Guthrie Honorary Symposium, June 6-9, 2011, Montreal, 248-254.