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Iron and Steel Metallurgy—Ongoing Challenges

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Abstract: Iron and steel making lasts for several thousand years and is based on changing technologies. The driving forces for those changes are economical or disposability of raw material and energy sources. In this paper three challenges for the newly development in iron and steel metallurgy are highlighted: Continuous casting strand size increase, solidification behaviour of new steel grades, and suppression of CO_2-emission during iron making. Examples underline the recent process of technological changes. 40 years of Sino German university cooperation in metallurgy are part of those technological development.

Keywords: Sustainable iron and steel production, continuous casting, transformation, CO_2-emission

1. Introduction

Metal products and the appropriate metallurgy help to develop culture and human life since thousands of years. At all times the responsible use of energy was one of the most important driving forces of the development of metallurgical processes because energy is directly related to the prices of the final products.

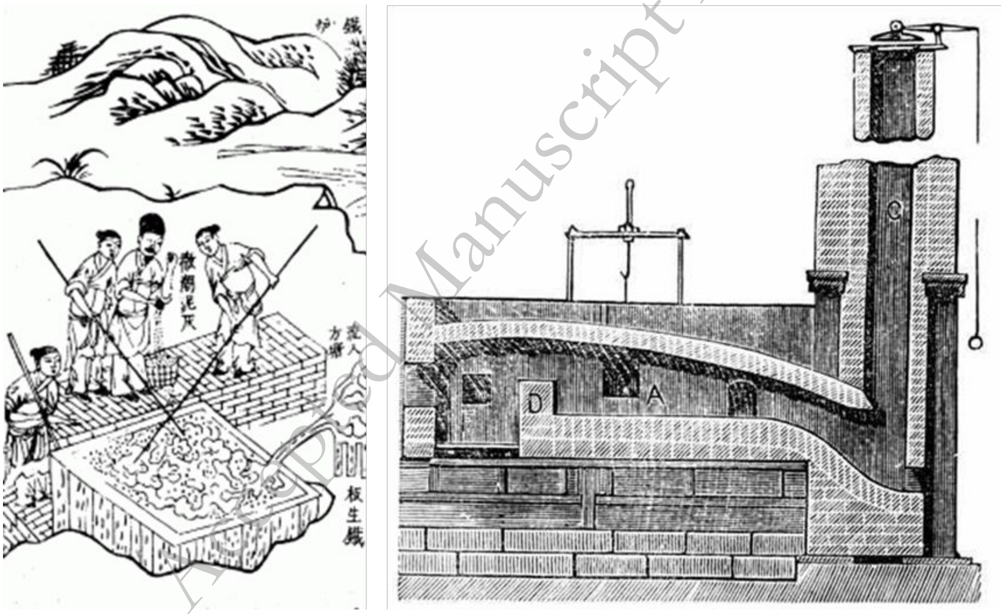

Fig. 1. Left side: Ancient Chinese puddling furnace [*] Right side: Longitudinal section of a puddling furnace, designed by Henry Cort (1784).

[*] *Chinese iron workers smelting iron ore to make pig iron and wrought iron. This illustration is only half of the picture showing the puddling process, while the right half (not shown) displays men operating a blast furnace. This illustration is an original from the Tiangong Kaiwu encyclopedia printed in 1637, written by the Ming Dynasty encyclopedist Song Yingxing (1587-1666). Picture taken from http://www.uni-tuebingen.de/uni/ans/project/conference/workshop.html. The picture also appears in Figure 14-10 on page 250 of E-tu Zen Sun and Shiou-Chuan Sun's translation of the Tiangong Kaiwu encyclopedia (Pennsylvania State University Press, 1966). [Remark in this source: "Not clearified"] Both pictures taken from: https://en.wikipedia.org/wiki/Puddling_(metallurgy)*

But not only energy influences the price of products but also the available resources and restrictions made the society of human beings. Those are restrictions in terms of environmental protection, sustainability, safety, or the intensity of demand for more products.

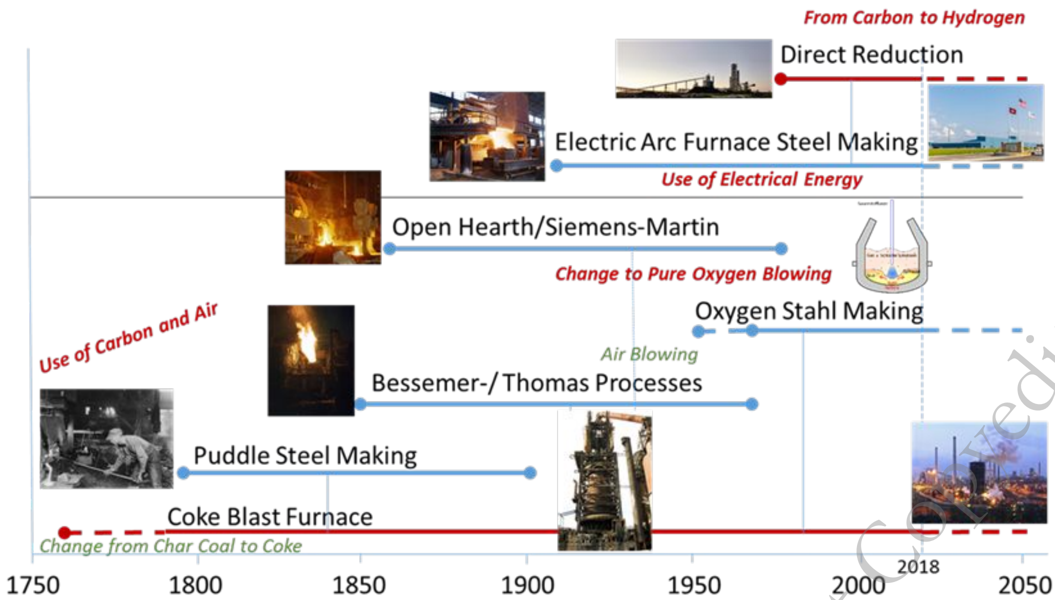

Fig. 2. Timeline of metallurgical production processes

The 'ongoing challenges' on metallurgy are also welcome tasks for technical researchers and businessmen, challenges to explore new ways of steelmaking with increased productivity and less specific energy consumption, act as pioneers in the field of productivity and economy. In many cases of significant improvement of metallurgical processes several persons worked on solutions in the same time period, but only a few of them are worldwide as famous as Mr. Abraham Darby I (coke oven blast furnace), Mr. Abraham Darby II and Mr. Henry Cort (puddling furnace, invented already during the Han Dynasty in China [1], Fig. 1), Mr. Sir Henry Bessemer and Mr. Thomas (steel converters), or Mr. Wilhelm Siemens and Mr. Pierre Martin (open hearth furnace).

In three examples some recent challenges are taken into focus including the question in which technical direction the further development is targeted to.

2. Challenges in casting of liquid steel, continuous casting of extreme shapes

CC machines for steelmaking have been invented since the 2nd half of the 19th century. But after a few careful operations after 1950, the industrial continuous casting (CC) process started to overcome the ingot casting technology in 1970. Today about 95 % of all the annually produced liquid steel is poured in the CC moulds; this totally more than 1,500 mio t. Let us take a look at the remaining 5 % of steel which is poured into ingots, in total nearly 100 mio t/y: There are very small lots of specialty steel of the size of 0.1 to 5 t each; there are orders of ingots with similar but varying chemical composition e. g. for watchmakers or for testing new steel grades´ properties; furthermore, big shapes for forging heavy beams for turbine manufacturing bound to electrical power plants, or also thick ingots to be shaped for very thick heavy plates. During the last 20 years the demands for increasing weights of those heavy as-cast semis stepped up because the architecture aimed for higher buildings, longer free spaces and extreme bridges. Manufacturing the respected number, pre-rolled slabs became expensive in comparison to smaller slabs from CC processes. The result of that development was a steady increase of extreme shapes, like sketched in Fig. 3.

A similar situation good be observed in the production of round semis: The number and sizes of high performance rings for the growing wind energy turbines increased; semis for ring rolling of those large bearing could be manufactured from large ingots, but the material efficiency of ingot casting is low compared to continuous casting. Also in this sector the tendency to cast large diameter semis became clear about 20 years ago, and today CC cast 1,000 mm rounds are industrially produced with high quality (Fig. 4).

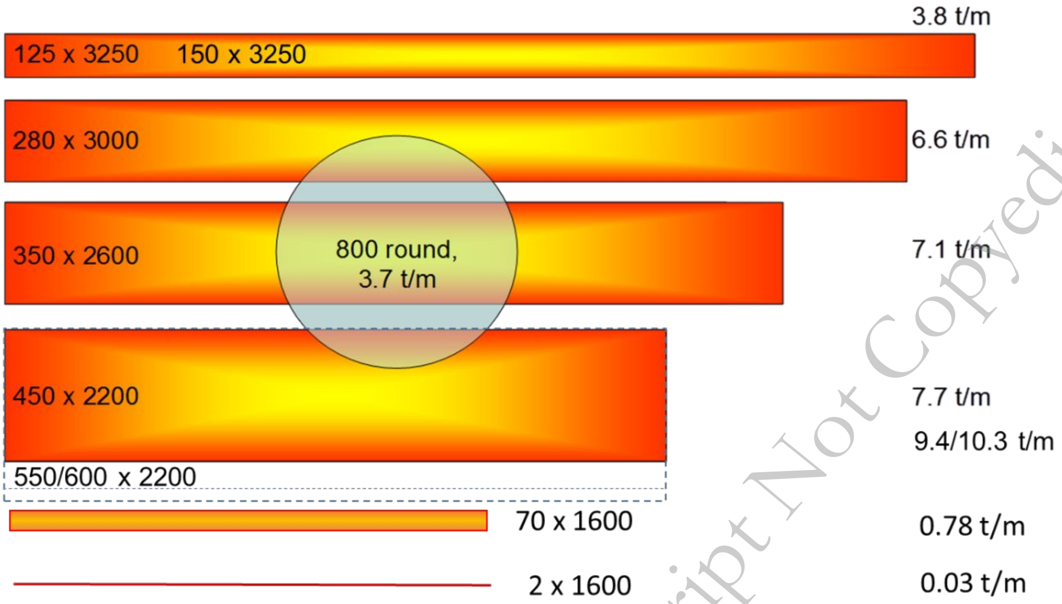

Fig. 3. Extreme shapes of continuously cast slabs for extreme wide and thick steel semis.

A strongly driving company in the field of extreme heavy plate delivery is the German company Dillinger which started already in 1964 a CC based heavy plate production and which developed together with machine builders like sms group in Germany new, extreme casters, in terms of design or size. Also big CC machines for the production increasing diameters were designed and delivered by sms group, mainly by the daughter company Concast in Switzerland which was the first professional builder of continuous casting machines in the world, started by Junghans, Irving and Tanner in the early 1950´s [2].

In both cases the emerging and encouraged Chinese steel production demanded CC machines from all over the world, mainly from Europe, to change technological dreams to reality.

Looking closer to the metallurgical details of solidification of extreme shapes in CC processes the first fact of importance is that the time from pouring into the mould to complete solidification of the core increases with the square of the thickness of the strand. That means that we need extreme long metallurgical length in the casting machines and the length of the moulds or we decrease the casting velocity. The casting speed for a 300 mm round strand is about 0.8 m/min, but for the cast of a 1000 mm round the speeds drops to about 16 cm/min. In this case the oscillation effects at the strand surface, developed by Siegfried Junghans [3], change from 'regular formation of oscillation marks' to overlaid 'ripple formations' which can be observed at ingot casting where casting velocity is zero, only the rising of the liquid steel level in the ingot mould, the surface tension and the steel melt viscosity control the distances and shapes of solidification marks at the surface.

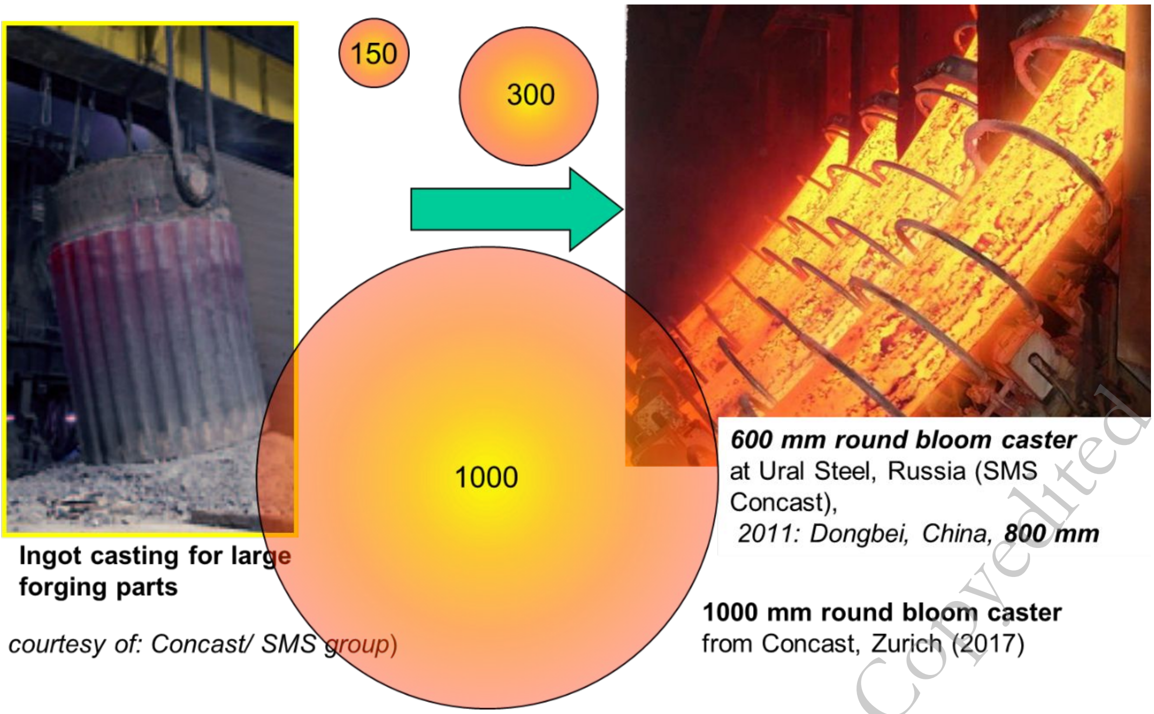

Fig. 4. Development cross sections of billets and large blooms, comparison of 150 and 1,000 mm rounds, and compared to a large ingot.

Some details of that behaviour have been studied by K.-H. Tacke [4], H. Jacobi and K. Schwerdtfeger [5] or P.J. Wray [6]. Further, the fluid flow in the mould, the melting and consumption of casting flux and the heat extraction at meniscus are also clearly influenced by dropping casting velocities [7].

3. Challenges in controlled solidification of new steel groups of steel grades

Another effect comes from the requirement and design of new steel grades. In the period of worldwide common research on the high Manganese steel grades with [Mn]>15 wt% and with elevated concentrations of Aluminium (up to 8 wt%) we observe poor ductility behaviour at strand temperatures in the range of solidification temperature (about 1350 °C) and unbending temperatures in the CC machine (about 900 °C). A number of mechanical stress acts to the strand like bending tension, inner pressure and tangential stresses, contraction stress from secondary cooling zones and others. The mechanical 'tolerance' or ductility of those high-Mn-steels are diminished by severe micro-segregation of several wt% between dendrite stems and interdendritic regions, and by divers groups of precipitates like MnS, Mn(S,Se), or AlN (Fig. 5). Depending on the concentration of [Mn], [Al], [N], [C], [S], and [Se], which was delivered by electrolytically produced Manganese metal for alloying, the sequence, shape, size and number of precipitates are varying.

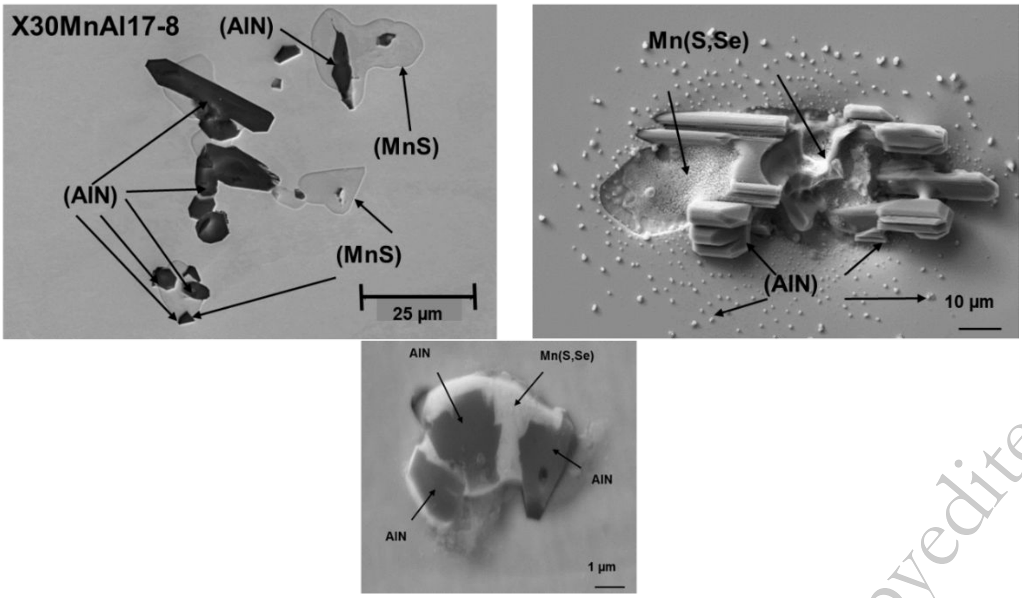

Fig. 5. Precipitates in HMnS (high Manganese steel grades). Remark nucleation points and growth of different types of precipitates.

Those precipitates disturb the material flow of the solid steel matrix at elevated temperatures and diminish the ductility (Fig. 6), so that surface and half way cracks must be avoided by modest casting operation, up to a changed design of the CC machine concern the cooling and unbending strategy. The high concentration of Aluminium influences also the development of the as-cast structure in a way, that CET (columnar-to-equiaxed-transition) zones disappear and columnar dendrites become long and seem to 'bend' in the corners of strands or ingots, when they come into competive growth with dendrites from the surface with the deflection of 90° [8]. Further, the high [Al] concentration reacts with the usually applied casting flux reducing the (SiO2) from the flux, increase the alumina content in the flux and change the viscosity behaviour of the lubricant drastically [9].

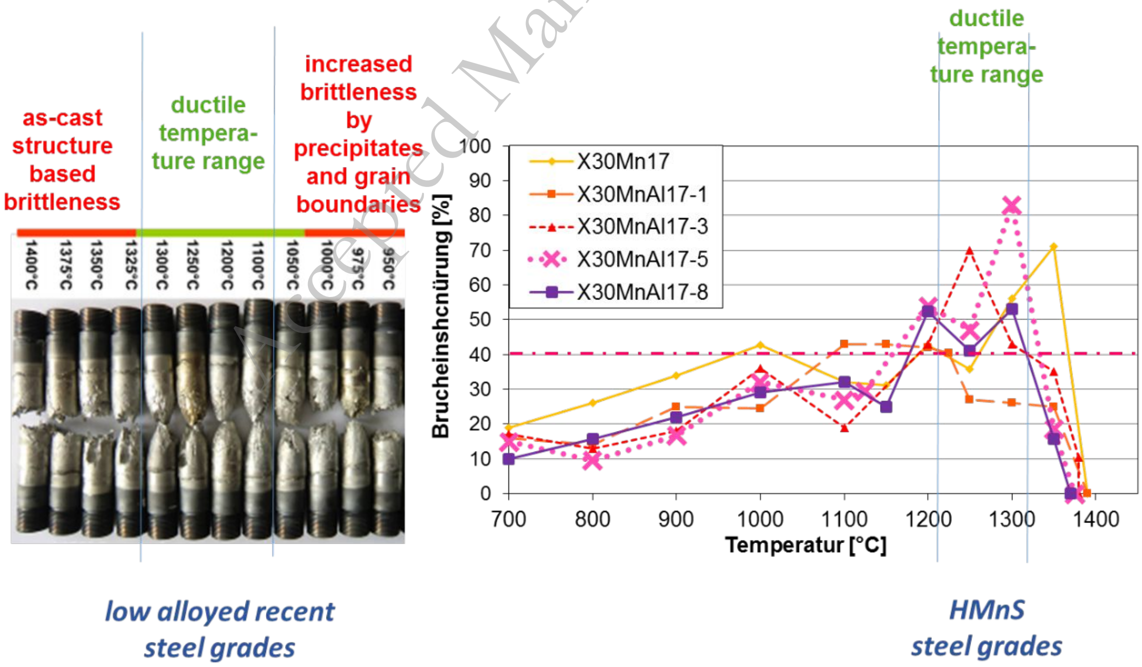

Fig. 6. High temperature tensile test as-cast steel samples and graphs of reduction of remaining area before cracking as a result of ductility investigation. [10]

4. Challenges in in iron making: suppression of CO_2 emission

In the last example the world steel production is affected because metallurgy of iron making is based since more than 200 years on the use of black coal and correspondingly coke. Since the concentration of the gas component {CO_2} in the earth´s atmosphere has been identified as the main driver of the global climate warming and scientists came to the conclusion that global warming of the atmosphere controls to natural growth, the large eddies and water currents in the oceans and so the local weather, political restrictions started to be given to all parts of the societies with aim to diminish the production of so-called "green-house gases". Here comes one of the most severe challenges to iron metallurgy which is to produce annually more iron metal and steel because it shall be needed to increase wealth and health of human beings by supporting mobility, growth of cities, production and distribution electrical energy for individual use; not possible without steel.

To remove the oxygen atoms from iron ore minerals for the formation of metallic iron a reduction gas is necessary which was and is {CO} from gasification of carbonaceous matter. Another reduction gas is hydrogen {H_2}. While carbon as a fossil material is store in the outer crust of the earth, hydrogen must be produced from H-bearing matter, such as natural gas CH_4 or water H_2O. In both cases energy must be applied to crack the molecules. So, the task to iron and steel industry is to change their production network from carbon based metallurgy to hydrogen based metallurgy because the reduction off-gas in the case of hydrogen use consists of water steam and condenses back to the resource water; hydrogen can be recycled by strong input of energy. This energy must be provided from sources not producing more {CO_2}; the use of natural resources like wind power, water power and sun light are the so-called renewable energy sources. In all of those cases a steel bearing infrastructure is necessary to form electrical power or heat from the renewables and distribute it.

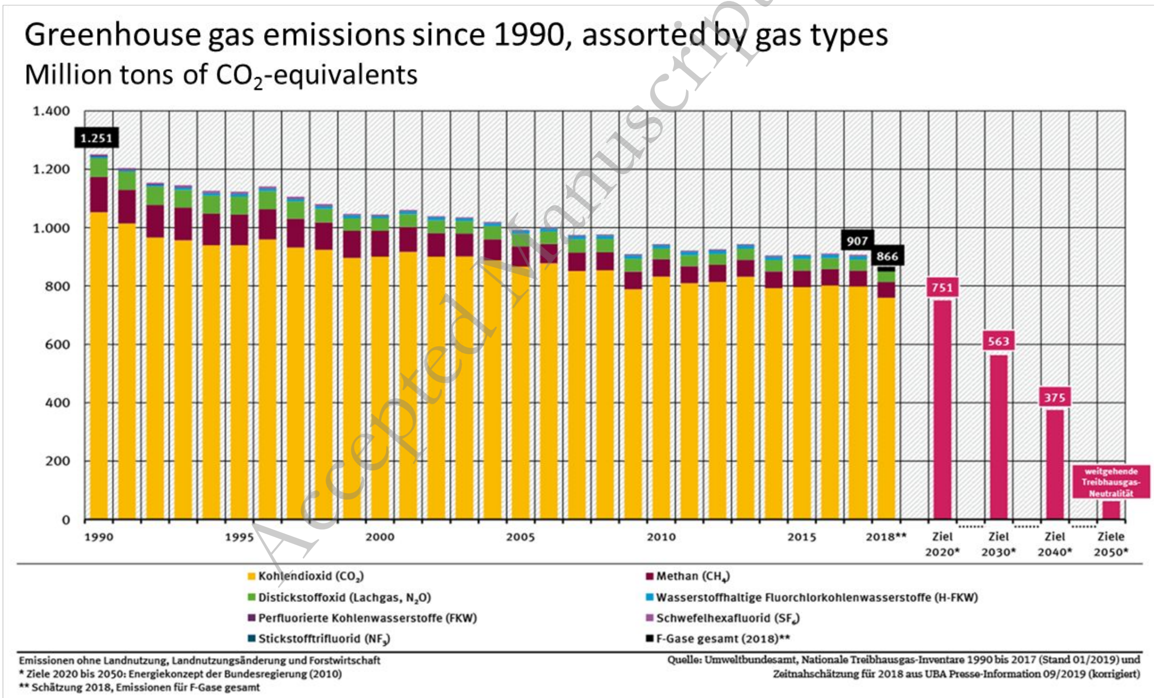

Fig. 7. Chart on development of {CO_2} equivalent gas emission in Germany from 1990 to 2018 and planned course until 2050.

As an example for the time-line for the technological change a chart from the German Office for Environmental Affairs is shown in Fig. 7. The {CO_2}-equivalent emission including natural gas, nitrogen-oxide and other gases acting like carbondioxide are to be diminished from 1,253 mio t/y in 1990 to 50 mio t/y in 2050 [11]. In 2018 the intermediate value of 866 has been reached. On the one hand, the steel industrial emission is only one part of the total {CO_2} emission and mobility and warming of the buildings are also responsible of the concentration of the green-house gases in the atmosphere on the other hand, but iron making is a significant part it.

Many companies are working right now with help of support of public foundations to develop and test the industrial application of so-called direct reduction processes (iron making on the basis of hydrogen) and new and adapted melting processes, but we must take into account that the electrical power is not so easy to store and to use as coal is. A lot of research work has to be done, and it is the task to solve all technical problems in relative short time. The bundled, common research and development of all concerned nations and companies will be necessary to make sure the iron production in the future on our planet without negative impact on the sensible behaviour of the planet´s nature.

The best researchers from universities in Europe, Asia and Americas are to be claimed to support the great global challenges in material production without negative input on our common planet.

5. Summary

In three examples some recent "ongoing challenges" on the metallurgical development has been shown. The changing architecture of buildings and infrastructure defines the demand on new semi-products coming from continuous casting. Especially thicker strand are requested, and there are new demands on continuous casting machines and operation parameters. New steel grades with combination of extreme properties are already designed in labs, the challenge to metallurgy is to produce those steel grades at demanded quality and competitive prices. In the last example the most serious point had been discussed: The making metallic iron without use of coal for the reduction of iron ore. In a relatively short time of only 30 years the complete iron making business should be changed from blast furnace technology using black coal and coke to a technology which will be based only on the use of specially produced hydrogen on the basis of regenerative energy sources.

Only the common global research of the centers of investigation like European, Asian and American universities and companies can fulfill this demand. The fruitful cooperation between Key State Laboratory at USTB and the RWTH Aachen University is a testimony for this responsibility since 40 years.

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