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## Book of Abstracts



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**Blast furnace ironmaking / 2**

## **HOW IRON ORE MELTS IN A BLAST FURNACE. PART 1: FERROUS BURDEN, SLAG FLOODING, PRODUCTIVITY**

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The present paper describes how the ferrous burden melts in a blast furnace and what consequences it has for blast furnace operation. For high PCI and high productivity operations, gas flow to and hence heat transfer from bosh gas to the solid/cohesive state of the ferrous burden is the rate limiting step in processing the ferrous burden, since the heat requirement of the direct reduction reaction of FeO determines the rate of heating of the primary slag. The processing and drainage of the liquid primary slag is determined by the FeO content of the slag, the slag composition and the voidage available in and below the cohesive zone. The iron fraction of the ferrous burden can only drain to the hearth once the direct reduction reaction is completed, since carbon dissolves in iron only when there is no FeO present. Analysis of operating blast furnaces shows that slag volume per ton is affecting productivity as well as maximum achievable coal injection rates. An estimate is that a decrease of slag volume of 10 kg per ton hot metal increases productivity by about 1,5% and reduces the metallurgical coke rate by 2-4 kg/tHM, while total fuel rate is reduced only by about 0,5 kg/t..

**Blast furnace ironmaking / 3**

## **HOW IRON ORE MELTS, PART 2: ROLE OF COKE AND NUT COKE**

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The present study was undertaken to find out whether or not there is an optimum distribution for nut coke and metallurgical coke over the ferrous layer and coke layer respectively. To this end a model for degradation of coke in the blast furnace was developed. It was verified with data from tuyere raking experiments. The tuyere raking result can be estimated based on degradation as a consequence of abrasion and direct reduction. Subsequently the model was used to analyze the optimum quantity and size for coke and nut coke. For operation at high PCI rates a large part of char is consumed in the direct reduction of FeO. Therefore, the higher the PCI rate, the lower the “consumable” nut coke rate. At a PCI level of 200 kg/tHM, the direct reduction consumes about 55 kg of coke. Since coke reacts on the surface of the particle, the direct reduction can be expressed as a diameter decrease, which corresponds with about 2 mm decrease of diameter. This means that all particles < 2 mm will be consumed by direct reduction. The model indicates that the voidage available for draining the liquid (“primary”) slag increases if more coke is put in the coke layer and less nut coke is used in the ferrous layer, which means, that at higher PCI rates the coke screen size has to be reduced. A strategy for setting the coke screen size is proposed.

**Blast furnace ironmaking / 4**

## **COPPER STAVE BENDING IN BLAST FURNACES**

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Copper staves are used in blast furnaces to protect the steel shell from process heat loads. Staves have experienced premature failures such as cracks, broken water pipes/water leakage, and abrasion related wear. Relationships between copper stave failure and stave deformation have been reported in literature. A detailed assessment methodology is presented to estimate the thermomechanical bending in a copper stave. This approach incorporates temperature-dependent copper properties, such as creep and plasticity to more accurately capture stave deformation under transient and cyclic thermal loading. The resulting deformations are compared with commonly reported stave failures. Improvements to stave design and the related anchoring system can be assessed using the assessment methodology presented.

**Blast furnace ironmaking / 6**

## INNOVATIVE DESIGN OF KALUGIN TOP COMBUSTION STOVES

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Heating of blast has been and remains one of the most important parameters which determine the economic efficiency of blast furnace production. However, for several decades the maximum level of blast temperatures remains unchanged (1200-1250°C). This shows the limited capacity of conventional hot stoves with internal and external combustion chambers. The paper presents a new unique design of top combustion stoves, i.e. Kalugin Shaftless Stove. These stoves make it possible to achieve the hot blast temperature of 1300-1400°C with the use of standard refractory materials (silica, mullite-corundum and fireclay bricks) and provide high economic and environmental performance with the service life of 30 years. In these stoves gas combustion is performed by pre-chamber type burner with jet and vortex supply of gas and air. The burner is installed at the top of the dome and provides full combustion of gas without flame pulsation before its entrance to the checkerwork and uniform distribution of combustion products over the checkerwork. These stoves have small dimensions, which effects a saving of 30-50% on refractory materials. Moreover, they can be used for reconstruction of existing hot stoves and installed instead of old stoves on the same foundation. At present more than 200 Kalugin Shaftless Stoves are successfully operated at iron and steel works in China, Russia, Ukraine, India, Japan, Kazakhstan, Indonesia, Turkey, Brazil, Syria and Czech Republic.

**CO2 reduction and energy saving / 7**

## ENERGY SAVING TECHNOLOGY FOR LOWERING AIR LEAKAGE OF SINTERING MACHINE

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In operational practice of the iron ore sintering machine, the increasing air leakage ratio will cause the higher electricity consumption of the suction fan, the higher solid fuel rate, the lower sinter productivity, and the worse sinter quality. In general, more than 50% of the leakage occurs at the pallets themselves and the interfaces between the pallets and the wind boxes. Basically, the sintering strand is comprised of a large number of pallets. And, it leads to the larger number of sealing parts. Consequently, the routine examination of the sealing condition of the pallets for detecting any abnormal air leakage is quite heavy load for the maintenance staffs. Hence, an on-line continuous measurement technology on the air leakage ratio of the sintering machine has

been developed in China Steel Corporation (CSC). It has been applied to help the maintenance staffs easily and effectively find out the abnormal air leakage, then to repair or replace the pallets in the very short time. In this technology, the hot-wire type anemometers are fixed on a moving rack for scanning the velocity of the effective air flowing through the sinter bed. Meanwhile, the microphones are installed beside the pathway and close to the outer sidewall of the travelling pallets for monitoring the sound pressure generated by the abnormal air leakage. For identifying the passing pallet, the thermal-resistant type RFID technology is adopted. Based on the data measured from the hardware system mentioned above, the air leakage ratio of the sintering machine can be calculated with the mass balance method and total gas flow rate drawn by the suction fan. And, the pallets with abnormal leakage can be detected and ranked in the severity of leakage according to the measured sound pressure with the relevant criteria. This technology had been implemented in the CSC No. 2 sintering plant since August, 2016. The operation result indicates that it can effectively reduce the air leakage ratio by 5% and further decrease the electricity consumption of the suction fan for the sintering machine. In fact, this technology is very helpful to maintain a low air leakage ratio during the long-term operation of sintering machine.

## Cokemaking / 9

### NEW COAL BLENDING TECHNIQUE FOR CONTROLLING COAL COMPATIBILITY BASED ON SURFACE TENSION OF SEMI-COKE

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Reasonable selection of coal brands and blending them for preparing raw material of coke are important to achieve the effective utilization of caking coal and enhancement of coke strength. Coal compatibility, namely “blending effect” has long been an unresolved problem. The effect is deviation between actual strength of coke made from coal blend and estimated strength which is calculated by averaging single coal properties. To understand the effect and develop a new blending technique which can control coal compatibility, we focused on surface tension of softening coals which probably affects adhesion phenomena between coal particles. However there is no method to measure the surface tension of coal at softening temperature. In this study, to overcome this difficulty, we devised a method to measure surface tension of semi-cokes obtained by heat treatment of coals at 500°C as a substitute for softening coals. First, we investigated the relationship between strength of coke made from binary coal blend and difference in the surface tension of semi-cokes made from these coals. As a result, the larger difference in the surface tension between two coal brands, the lower strength coke was produced. Next, the finding was extended to multi-coal blend. The strength of coke was deteriorated with an increase in interfacial tension which is a new proposed factor calculated from the surface tensions of single coal brands used in the coal blend. The blending technique based on interfacial tension enables us to evaluate more precisely the coal compatibility and to select the good combination of coals, which can contribute to the production of high strength coke and effective usage of coking coal resources.

## Sintering / 10

### APPLICATION OF CRYSTALLOGRAPHY TO THE THERMODYNAMIC MODELLING OF SILICO-FERRITE OF CALCIUM AND ALUMINUM

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It is important to understand solid-liquid equilibrium of Al<sub>2</sub>O<sub>3</sub>-CaO-Fe<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub> system to understand the sintering reaction, although the sintering reaction is a non-equilibrium and inhomogeneous. Phase equilibrium calculation of this system has some problems, such as thermodynamic models for some silico-ferrite of aluminum and calcium phases were not present. Thermodynamic modeling of SFCA, Ca<sub>2</sub>(Fe,Ca,Al)<sub>6</sub>(Fe,Al,Si)<sub>6</sub>O<sub>20</sub> was conducted in the framework of the Compound Energy Formalism (CEF). Preferred substitution of Al in tetrahedral site was observed by Fe and Al *K*-edge X-ray absorption near edge structure. On considering crystallographic information in particular the charge compensation relation in the SFCA solution, the Ca<sub>8</sub>(Fe<sub>3+</sub>)<sub>20</sub>Oct(CaSi<sub>6+</sub>,FeFe<sub>6+</sub>,FeAl<sub>6+</sub>)<sub>3</sub>paired(CaSi<sub>6+</sub>)<sub>1</sub>paired(Fe<sub>3+</sub>,Al<sub>3+</sub>)<sub>20</sub>TetO<sub>80</sub> structure was considered as the SFCA solution model. By using this new model, SFCA single phase region can be well described in the phase diagram of the Ca<sub>4</sub>Si<sub>3</sub>O<sub>10</sub>-CaFe<sub>6</sub>O<sub>10</sub>-CaAl<sub>6</sub>O<sub>10</sub> system.

**Postersession and Coffee Break / 16**

## RESEARCH ON THE LONG LIFE BLOWPIPE LINER OF BF AIR SUPPLY APPARATUS

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The blowpipe of blast furnace (BF) air supply apparatus is always the weakest link of the hot blast pipe system. The local air leak, high surface temperature and short service life of blowpipe were ubiquity in the air supply apparatus after being used for a period of time. The average service life of No.2 BF tuyere blowpipe with conventional liner in Shouqin Company was 250 days at the initial stage of blowing-in. By improving the lining materials, the tuyere blowpipe adopted the molten silica-based composite refractory as lining material so that the thermal conductivity decreased from 0.812 W/ (m•[U+2103]) to 0.381 W/ (m•[U+2103]). Finally, the average service life of the tuyere blowpipe increased up to 702 days, which was twice times more than before, providing guarantee for the stable production of blast furnace

**Blast furnace ironmaking / 17**

## FUNDAMENTAL INVESTIGATION OF COKE MIXED CHARGING USING DISCRETE ELEMENT METHOD

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To achieve stable operation of coke mixed charging, it is essential to control coke segregation behavior in mixed layer. In this study, the effect of charging conditions and burden particle diameter of mixed coke ratio at blast furnace top were analyzed by numerical model based on discrete element method. Parameters necessary for calculation were optimized by experiment and calculation. Then, segregation behavior of coke particle was numerically investigated by using above calculation parameters. As a result, following findings were obtained. 1) At reverse tilting and broad range charging pattern of rotating chute, granular flow to the furnace center



was interrupted and mixed coke particle was distributed uniformly for the direction of furnace radius. 2) Coke segregation in mixed layer was decreased by lowering particle diameter ratio between coke and sinter. Therefore, for the improvement of coke mixed ratio in mixed layer, control of particle diameter of coke and sinter is effective.

### Keynote / 18

## PRESENT STATUS AND FUTURE PERSPECTIVE OF IRONMAKING IN CHINA

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During last few years, iron production in China was kept at about 700 million tons annually, which was totally produced from BF process. At same time, a lot of mini BFs have been eliminated, and many big BFs have been built up and put into operation. There are 23 BFs with inner volume equal or over 4000m<sup>3</sup>. Both sinter machines and pellet facilities have been enlarged and upgraded correspondingly. Iron burden constitute has been shifted to 70% of sinter, 15-20% of pellet, and 10-15% of lump in general. Under the conditions of frequent changes in raw material quality and big economic pressure, BF operation controls have been improved in many aspects to maintain stable operation indexes, and to realize low cost production. Many new techniques and facilities have been developed and applied in ironmaking process, including new sealing technique of sinter machines, straight grate pellet process, Ti-Mg bearing pellet, and BF monitoring devices. There is significant progress in cleaning production. Strict emission standards have been imposed on all steel works. Various desulphurization facilities have been installed to treat sinter flue gas. Many open raw material yards have been modified to complete closing ones for dust emission control. Casting areas of blast furnaces have been sealed efficiently. Iron production in China is expected to be reduced gradually in the future, due to overcapacity control of steel production and more recycling of scrap. There is a big room for Chinese ironmaking improvement, including upgrading efficiency of BF ironmaking process, reducing BF fuel rate, extending BF campaign life, and pollution control further. Developing and application of BF smart control systems, by means of various artificial intelligence techniques, are hot points in our industry in the future. CO<sub>2</sub> emission control will be a big challenge for current BF process. New ironmaking processes will be explored continuously.

### Modelling and simulation in coke and ironmaking / 19

## IMPACT EVALUATION OF METALLIZATION DEGREE OF PELLETS FOR DIRECT REDUCTION ON ITS VALUE IN USE

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Direct reduction and electric arc furnace are important routes for steel production in the world. The DRI production in 2016 was 72.8 Mt, from which 64.8% was by Midrex Process, 17.5% by coal-based, 17.4% by Hyl/Energiron and 0.3% by Other processes.

The metallic charge of direct reduction is mainly composed by iron ore agglomerate in the form of pellets and the direct reduction of iron ore occurs without melting and using natural gas as reducing agent. As a consequence, this process is widely used in countries where natural gas cost is low.

Pellets chemical and metallurgical specifications are very important for direct reduction process and steel refining in electric arc furnace. These characteristics impacts on reactor's productivity

and consumptions of natural gas, electricity, flux and electrodes and consequently on steel cost production.

The paper presents a discussion about the impacts of metallization degree of pellets for direct reduction on their value in use. Value in use is the maximum price that a particular company is willing to pay for a replacement material without deteriorating economic results. A mathematical model which simulates DRI and steel production by direct reduction and electric arc furnace route was developed using mass and heat balance and also empirical correlations from literature.

#### Postersession and Coffee Break / 20

### STUDY ON THE MECHANISM OF THE FLUE GAS CIRCULATING SINTERING PROCESS ON SINTER PROPERTIES

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The flue gas circulation sintering process can not only realize the comprehensive utilization of resources, but also can realize clean production which by recycling sintering flue gas to conduct iron ore sintering and significantly reducing the flue gas processing in the terminal treatment. The flue gas directly recycling use in sinter production will affect the sinter properties, because the flue gas oxygen content and temperature in the bellows are different. In order to make rational use of the sintering flue gas, it can be divided into high temperature flue gas, high pollution flue gas and comprehensive circulating flue gas according to the characteristics of sintering flue gas. In this paper, sintering cup experiments are used to study the influence law of the flue gas temperature, the oxygen content, the circulating sintering time and the carbon amount on sintering technical indexes and sintered ore metallurgical properties. The experimental results show that the reasonable amount of carbon reduction is 5% to 10% when the flue gas sintering in the circulation temperature is 423K to 523K [U+2103]. To guarantee the sinter properties, the oxygen content of flue gas should not be less than 18% and the reasonable time of flue gas circulation sintering about 6 min when the circulation flue gas is 473K and the carbon content is 4.05%.

#### Blast furnace ironmaking / 21

### NO RETURN FINE BF IRONMAKING PROCESS

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A large quantity of return fines recycling is a serious shortage of current sinter + BF ironmaking process, which causes big increases in sintering operation cost and pollutant emissions. No Return Fine (BF) Ironmaking Process (NRIP) is conceived to use return fines in BF directly, after removing minus 1 mm part of dust from it. NRIP could make sinter+BF ironmaking process more efficient and environment friendly. The key point of NRIP application is to enhance capacity of BF granular burden acceptance. The methods are supposed to be dust removing control, separately charging of different size of iron ores, optimum burden distribution, gas flow control, sinter RDI control, smart ironmaking, etc. Industrial practices around the world have demonstrated firm basis and the feasibility of NRIP application.

**Blast furnace ironmaking / 26**

## **ON-LINE THICKNESS MONITORING SYSTEM OF COPPER STAVES IN BLAST FURNACE IN CSC**

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Modern blast furnace with long campaign life will install copper stave as its cooling element in bosh, belly and low shaft area. However, copper is not a good material for wear-resistance and deformation-resistance. The wears caused by burden material or high heat load damage make the stave thinning and leakage. Therefore, blast furnace with copper stave has to focus on its thickness. This study describes a new technology to evaluate stave thickness by using body temperature algorithm. It can monitor thickness real time and comprehensive. The system have installed on site in CSC to monitor the thickness of copper stave.

**Cokemaking / 28**

## **EFFECT OF IRON ORES ON THE COKING PERFORMANCE OF FERRO-COKE**

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Highly-reactive coke can improve the reaction efficiency of blast furnace, as well as decrease the reduction agent ratio and CO<sub>2</sub> emission. Ferro-coke, which is obtained by combining coal with iron ore during coking, has been studied as a novel highly-reactive coke. In this study, effect of three iron ore types (limonite, hematite and oolitic hematite) on the gas generation, volume behavior, and composition evolution during coking were investigated using thermal gravity, high temperature microscope and X-ray diffraction, respectively. The change mechanism of the coking performance of ferro-coke according to the type and content of iron ore were discussed in detail. In addition, the interaction between iron ore and coal was also investigated. The experimental results have guiding significance for the development of the fabrication process of ferro-coke.

**Pelletising / 29**

## **A NEW 3D CHARACTERIZATION TECHNIQUE FOR MINERALOGICAL STRUCTURE OF IRON ORE PELLET**

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With the rapid development of iron and steel industry in China, the iron ore pellet as an essential raw material plays an important role in the blast furnace. Due to large-scale production of iron ore pellet, microscopic characterization is an important step in quality control. The structure and distribution of minerals in a pellet and the bonding types at point contacts between the grains strongly affect its metallurgical properties, like mechanical strength and reduction performance. Traditionally, pellets are characterized by 2D Optical Microscopy or Scanning Electron Microscopy. However, these approaches cannot be used to observe inner interconnection crystals in the volume space. Therefore, the mineral information is incomplete and the 3D morphology and spatial distribution of the minerals are unknown. In this work, a new 3D characterization methodology based on serial sectioning of digital microscopy and image analysis was developed, automating some steps of the characterization. The discrimination of the main solid phases such as hematite, magnetite and silicates, and of pores can be achieved by threshold segmentation in 3D space. This approach enables the acquisition of high-resolution images in a cost-effective manner and greatly assists in the further study of the microstructure of the minerals in an iron ore pellet. The results of this study will contribute to further understanding of the mineral morphology effects on the properties of pellet.

**Postersession and Coffee Break / 31**

## **EFFECT OF SILICO ON THE METALLOGENIC AND REDUCTION MECHANISM OF THE LOW-QUALITY IRON ORE SINTER**

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Under the pressures of the decreases of high quality iron ore, the iron and steel enterprises in China turn to use low-quality ores which contain elements such as much silicon, aluminum, et al, in sintering. In order to understand the metallogenic and reduction mechanism of the low-quality iron ore sinter, in situ test were used in this study. The sinter samples were analyzed by X-ray diffraction, scanning electron microscopy and mineralogical microscopy to explore the effect of silicon and aluminum on the formation of complex calcium ferrite during sintering. In addition, the characteristics of the gas-soild reduction reaction between complex calcium ferrites and CO gas were studied by thermogravimetric analyzer. The effect of silicon and aluminum on the changes of mineral composition and microstructure of complex calcium ferrite during the isothermal reduction process was also investigated. The results of this study will help to the efficient utilization of low quality iron ore in sintering process.

**Pelletising / 32**

## **REDUCTION BEHAVIOURS OF PELLET BY HYDROGEN AND CARBON MONOXIDE ATMOSPHERES USING IN-SITU XRD AND THERMOGRAVIMETRIC ANALYSES**

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Canadian hematite acid pellet with low magnetite content fluxed and olivine were isothermally reduced with hydrogen and carbon monoxide at 600 to 1000 [U+2103]. The course of reduction was investigated by measuring the oxygen weight loss as a function of time using a thermogravimetric analysis. Macroscopic and microscopic examination, X-ray and carbon analyses were also used to elucidate the mechanisms of reduction of pellet. For CO atmospheres, CO content in mixture can stimulate carbon deposition behaviors in pellet reduction procedure and carbon deposition

leads to the fracture of pellet at the low temperature. For H<sub>2</sub> atmospheres, temperature from 600 to 700 and from 900 to 1000 °C have more influence on reduction fraction than one from 700 to 900 °C due to dense microstructures of pellet forming in the latter. Reduction of Fe<sub>2</sub>O<sub>3</sub> to Fe<sub>3</sub>O<sub>4</sub> is fastest and reductions of Fe<sub>3</sub>O<sub>4</sub> to FeO and FeO to Fe happen at the same time. Pellet reduced by CO has porous structures, while pellet reduced by H<sub>2</sub> has a dense product layer on the surface.

#### Cokemaking / 34

### THE IMPROVEMENT OF GAS COMBUSTION IN JFE FUKUYAMA 5D

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JFE Fukuyama No.5 D battery, since this battery started up, we struggle to control the temperatures of center flues and they fall to a low level. We estimated that the amount of air flow in center flues is less than gas flow because of the oven structure. Then, we entertained the way to increase air flow and invented the way we insert air with C ports which are used in only C gas inflammation. In this experiment, we simulated the changes of oven wall temperatures in inserting air and did at the actual equipment. As the result, we made sure of temperature rising nearly similar to our simulation. In this experiment, we put gas concentration meters in target flues and the concentration of CO is extremely less compared with before inserting air. So we resulted that gas in the center flues was burnt completely. As it is now, we flow air excessively to all flues due to covering the amount of air flow in the center flues. We can modify the air ratio by this improvement. So it attribute to reduce the amount of combustion gas and the heat consumption. Now we are going to conduct the equipment for inserting air to all center flues.

#### Blast furnace ironmaking / 35

### A MULTI-COUPLED TRANSIENT MODEL FOR NUMERICAL SIMULATION OF BLAST FURNACE PROCESSES

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A multi-coupled three-dimensional transient model is proposed for simulation of blast-furnace (BF) iron-making processes. The model couples the whole thermo-fluid flow regions in the BF internal, including shaft, belly, hearth and raceway. Furthermore, the internal fluid flow, heat/mass transfer process is coupled with the heat transfer taking place in the outside refractory walls enclosing the BF internal fluid domain. The coupled simulation of processes in BF upper, middle and bottom parts, and fluid-solid conjugate heat transfer approach adopted in this model allows one to avoid applying artificial boundary conditions between different regions of the BF. The model is validated against the temperature measurements by the embedded thermal-couples, and the cross-sectional temperature measurement at the BF throat. Very good agreement is achieved for temperature at thermal-couple sampling locations, between the measured and calculated temperatures.

The model is capable of predicting transient behaviour of BF processes, such as non-uniform descending velocity of burden, time-varying distribution of different burden materials (coke, pellet, ore and sinter), distribution of porosity, cohesive zone. Distributions of temperature, pressure, velocity and volume fractions of gas mixture, solid particles, liquid iron and slag. The model is applied for detailed analysis of BaoSteel's No. 2 BF in the Baoshan base, Shanghai.

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## COKE DEGRADATION AFTER REACTION WITH CARBON DIOXIDE IN BLAST FURNACE USING NMR GAS IMAGING

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Coke degradation by the reaction with carbon dioxide is known to cause the fine particle generation, deteriorating gas and liquid permeability in a blast furnace. Coke degradation must be suppressed or controlled in order to achieve stable operation of blast furnace. In this study, the mechanism of the coke degradation by the reaction with carbon dioxide, i.e. solution loss reaction, was investigated using our developed NMR gas Imaging technique in terms of changes in reactivity of cokes and fine particle generation after mechanical impact by I-drum revolutions when coke qualities were changed. In conclusions, (1) In case that the reaction ratio of coke with CO<sub>2</sub> is changed up to the reactivity of cokes, the reactivity of the cokes strongly affects the fine coke particle generation from reacted cokes. (2) In case that the reaction ratio is adjusted to predetermined value (20mass% in this study) as observed in actual blast-furnace operation, the increase in fine coke particle generation due to the reaction appeared unchanged, regardless of the reactivity of cokes. Instead, the coke abrasive strength appears to significantly affect the fine coke particle generation from reacted cokes.

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## EXPERIMENTAL STUDY ON TREATMENT OF COREX DUST BY COLD BOND PELLETIZING

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COREX shaft furnace dust contains large amounts of valuable elements, such as iron and carbon, and compared with blast furnace dust, it contains more metallic iron. Therefore, take appropriate process to recycle the COREX dust can further achieve efficient utilization of resources. The chemical composition, particle size distribution, microstructure and mineral composition of the dust were characterized by chemical analysis, particle size distribution analyzer, scanning electron microscopy (SEM) and X-ray diffraction (XRD). Carbon-bearing cold-bonded pellet was prepared by COREX dust and further reduced to study the effect of C/O molar ratio, reduction temperature as well as reduction time on the reduction. Results showed that with the increase of C/O, reaction fraction increased first and then decreased; the metallization rate showed a gradual increasing trend with the increase of reduction temperature and reduction time. The optimum process parameters were obtained and as follows: reduction temperature, 1300 [U+2103]; reduction time, 15 minutes and C/O molar ratio, 1.2. Under such conditions, the metallization rate reached to nearly 80%, which showed the feasibility of recycle COREX dust recycling by cold bond pelletizing.

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## EFFECT OF ORDINARY MAGNETITE RATIOS ON PROPERTIES, PRODUCTIVITY, AND STRENGTH OF HONGGE HIGH-CHROMIUM VANADIUM-TITANIUM MAGNETITE SINTERS

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The influence of ordinary magnetite ratios on Hongge high-chromium vanadium-titanium magnetite (HCVTM) sinters was researched through sintering pot tests. The researches including yield, sintering ratio, tumbler index (TI), productivity, solid fuel consumption, reduction degradation index (RDI) and reduction index (RI) were tested and calculated. The addition of ordinary magnetite ore is an adjusting method to affect the chemical content and properties of sinter. In this work, with ordinary magnetite ratio increases, the yield decreases from 90.5% to 84.6%, and sinter ratio decreases slightly from 84.98% to 83.43%. The maximum of productivity is 3.52 t[U+FOD7]m-2[U+FOD7]h-1 with 15% ordinary magnetite and then decreases with increases of ordinary magnetite ratio. The TI decreases and the minimum of TI is 43.65% with 45% ordinary magnetite. The RI increases from 50.7% to 70.9%, and the solid fuel consumption rises from 55.25 kg[U+FOD7]t-1 to 59.10 kg[U+FOD7]t-1 while the RDI deteriorates from 96.7% to 50.7% with increase of ordinary magnetite ratios.

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## EFFECT OF ORDINARY MAGNETITE RATIOS ON THE BASIC CHARACTERISTICS OF HONGGE HIGH-CHROMIUM VANADIUM-TITANIUM MIXED ORES

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The effect of ordinary magnetite ratios on the basic characteristics of Hongge high-chromium vanadium-titanium mixed ores was investigated through micro-sinter methods. The researches including assimilation characteristic, crystal intensity characteristic, bonding strength characteristic and fluidity characteristic were studied. With increase of ordinary magnetite ratios in Hongge high-chromium vanadium-titanium mixed ores, the lowest assimilation temperature (LAT) of mixed ores decreases slightly from 1395[U+F0B0]C to 1324[U+F0B0]C, the crystal intensity (CI) first decreases and then rises, and the minimum of CI is 4752 N with 30% ordinary magnetite. Meanwhile, the bonding strength (BS) decreases from 4152N to 1781N, and the fluidity index of liquid (FIL) rises from 0.035 to 0.14 with increase of ordinary magnetite ratio. The correlation of FIL with LAT and BC were negative.

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## NON-ISOTHERMAL REDUCTION BEHAVIOR OF CaO•Fe2O3 AND Fe2O3

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In the current work, the reduction route of CaO•Fe<sub>2</sub>O<sub>3</sub> (CF) was investigated and the comparison of CF and Fe<sub>2</sub>O<sub>3</sub> (H) on their reduction kinetics was made. Non-isothermal reduction experiments of powdery CF and H heating up to 1123K with a rate of 10K·min<sup>-1</sup> in a continuous stream of 30% CO and 70% N<sub>2</sub> were conducted through thermo-gravimetric analysis. It found that the reduction processes of CF and H begin at 873 and 623K, respectively. Reduction rate analysis and subsequent X-Ray diffraction measurements at various stages revealed that the reduction of CF can be divided into two steps (CF→C<sub>2</sub>F→Fe), whereas that of H mainly comprises three steps (H→M→W→Fe). Activation energy was calculated by Freeman-Carroll method and the average values of CF and H reduction are 49.88 and 43.74 kJ·mol<sup>-1</sup>, respectively. Model function was calculated by Malek method and the results indicated that the reduction of CF can be described by random instant nucleation and two-dimensional growth of nuclei model, its corresponding model function is Avrami-Erofeev equation with the integral form of [-ln(1-α)]<sup>n</sup>, whereas the

reduction of H was expressed initially by tertiary chemical reaction model ( $\alpha=0.1\sim 0.5$ ) with the integral form of  $1-(1-\alpha)^3$ , and subsequently by two dimensional cylindrical diffusion model ( $\alpha=0.5\sim 0.9$ ) with the integral form of  $\alpha+(1-\alpha)\ln(1-\alpha)$ .

**Cokemaking / 44**

## NEW UNDERSTANDING AND EVALUATION OF COKING COALS AND COKE PROPERTIES

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Evaluation of coking coal properties in coking Industry depends on several independent indicators tested in different test conditions for a long time, for example, Gieseler fluidity, Arnu-Audibert's dilatometer, plastometer indice, Roga index, and volatile content. On the other hand, evaluation of coke thermal properties depends on Coke Reactive Index (CRI) and Coke Strength after Reaction (CSR) tested in 1100[U+2103] and lasted in two hours. In view of the fact that there are some shortages of evaluation coking coal properties and coke thermal properties, the evaluation methods for "the related properties during carbonization of coking coal" and "the comprehensive thermal performance of coke" were developed. The former one was used to measure the relevance between the volatile matter escaping, plastic layer forming, and swelling pressure during single and blending coking coal carbonization process; the latter one was used to detect the initial temperature of coke reaction, the average coke reaction rate and the coke strength after reaction at the coke weight loss up to 25%, the dependence of the coke strength after reaction on the reaction temperature, the coke polycondensation index and coke strength after polycondensation for the coke weight loss up to 25%. These two methods can be used to further identify the performances of coking coal and coke, and establish some new evaluation methods of coking coal and coke quality.

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## THE DISTRIBUTION OF MAGNESIUM IN THE SINTERED PRODUCTS AND ITS EFFECT

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Flow and Occurrence of Magnesium in Sintered Products were studied by XRF and SEM-EDS. The results of this research are as follows. The figure shows magnesium content of sintered products in the following decreasing order: blast furnace return fine, sinter return fines, finished ore. Moreover, magnesium content in the 0.5mm-3.15mm size of blast furnace return fine is especially high. Magnesium content of sintered minerals is in the following decreasing order: magnetite, SFCA, silicate, hematite. Magnesium existing in the magnetite will generate magnesia magnetite, which prevents the oxidation of magnetite and then reduces the SFCA liquid phase. Magnesium existing in the SFCA will increase the viscosity of SFCA to reduce the bonding range of the liquid phase and may affect the crystallization state of SFCA, so it will deteriorate the strength index of sinter. The incompletely assimilated dolomites were found in the sintered products and the diffusion range of magnesium is wider than that of calcium, because the chemical reaction ability of calcium oxide is higher than that of magnesium oxide.



**Sintering / 48****ISOTHERM IN THE Fe-RICH REGION AND MgO PARTITIONING BETWEEN LIQUID SLAG AND Fe<sub>3</sub>O<sub>4</sub> ON THE FeO<sub>x</sub>-CaO-SiO<sub>2</sub>-MgO SYSTEM AT 1573 K UNDER OXYGEN PARTIAL PRESSURE OF 10<sup>-7</sup> atm****Author(s):** Dr. HAYASHI, Miyuki<sup>1</sup>**Co-author(s):** Dr. WATANABE, Takashi<sup>1</sup> ; Prof. SUSA, Masahiro<sup>1</sup><sup>1</sup> *Tokyo Institute of Technology***Corresponding Author(s):** hayashi@mtl.titech.ac.jp

The increment in the impurities of iron ore such as Al<sub>2</sub>O<sub>3</sub> lowers the reducibility of iron ore sinter and increases the gas permeability resistance in a blast furnace. In order to overcome the problems, MgO is often added into sinter by blending dolomite and/or serpentine as a constituent of raw materials of sinters. The role of MgO in sinter at the lower part of a blast furnace depends on the MgO distribution in sinter. In this study, liquidus in equilibrium with iron oxides in the FeO<sub>x</sub>-CaO-SiO<sub>2</sub>-MgO system has been measured at 1573 K and at oxygen partial pressures of 10<sup>-7</sup> atm and 10<sup>-6</sup> atm which is similar to that of the sintering process. In addition, MgO concentrations in the liquid and the FeO<sub>x</sub> phases have also been measured so as to elucidate the compositional dependency of the MgO partitioning between two phases. It has been found that the liquidus region in the FeO<sub>x</sub>-rich side is decreased by 5 mass% MgO addition over the measurement range of the C/S ratios between 0.32 and 2.28. The liquidus is also divided into two compositional areas of the silicate-based liquid and the calcium ferrite-based liquid, where the C<sub>2</sub>S phase becomes stable thermodynamically in the range of the C/S ratios between 1.66 and 1.96. The MgO content in magnetite is as large as 14 mass% at C/S = 1.62, and the partitioning of MgO in liquid phase decreases with increasing the C/S ratio.

**Postersession and Coffee Break / 49****STUDY ON TECHNOLOGY OF REMOVAL OF TITANIUM FROM HOT METAL IN BLAST FURNACE****Author(s):** Dr. ZHANG, Xuesong<sup>1</sup>**Co-author(s):** Mr. ZHAO, manxiang<sup>1</sup> ; Mr. LIANG, hailong<sup>1</sup> ; Mr. ZHAO, tieliang<sup>1</sup> ; Dr. ZHOU, jiliang<sup>1</sup><sup>1</sup> *ShouGang Group***Corresponding Author(s):** zhoujiliang@shougang.com.cn

Laboratory test of removal of titanium from hot metal is developed in different remover, different proportion and different granularity. The suitable remover and parameters for industrial production test are found. At the same time the removable titanium removal device is designed and developed. Industrial test of removal of titanium from hot metal in blast furnace of Shou-gang stock company is developed successful. When the ratio of the remover is 1%, the titanium removal rate of hot metal reaches above 50%. And the temperature drop and slag skimming amount are all within the normal range. There is no effect on the back process. Through this test, the contradiction between high titanium content in hot metal because normal furnace protection and low titanium content in hot metal of silicon steel is solved.

**Postersession and Coffee Break / 51****KINETIC ANALYSIS OF COKE DISSOLUTION IN CARBON – IRON MELTS****Author(s):** Dr. ZHANG, Wei<sup>1</sup>**Co-author(s):** Mr. GUO, Peng<sup>1</sup> ; Dr. HUA, Fubo<sup>1</sup> ; Prof. XUE, Zhengliang<sup>1</sup> ; Mr. GONG, Shushan<sup>2</sup> ; Mr. ZHANG, Wenhai<sup>2</sup><sup>1</sup> *Wuhan University of Science and Technology*<sup>2</sup> *Science and technology of flash ironmaking of Beijing, Co., Ltd., Beijing*

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Flash ironmaking is a new smelting reduction process. The extent of molten iron carburization is close to saturation in the blast furnace process. However, the extent of carburization in a flash ironmaking process is unexpected because there is no compression of solid charge and no carburization reactions occurred between the deadman bottom and hot metal. To this end, iron powder reduced and chemical pure graphite were used as raw materials, and the iron powder was heated up to 1855K by using a tubular resistance furnace, and the high-purity N<sub>2</sub> was used as the protective gas to study the kinetics of coke dissolution in molten iron. The experimental results show that discarding the change of "k" "t" with dissolution time, the values of "k" "t" were determined under experimental conditions in each group, 4.20×10<sup>-6</sup> m/s (First group), 5.28×10<sup>-6</sup> m/s (Second group) and 6.50×10<sup>-6</sup>m/s (Third group) under natural convection conditions. Considering the change of dissolution rate coefficient with dissolution time, the dissolution rate "k" "t" decreases with the increase of dissolution time and is only controlled by mass transfer, and also decreases with the increase of sulfur content in the iron bath.

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## STRENGTH OF INTERFACES IN METALLURGICAL COKE AND ITS INFLUENCE ON COKE ABRASION

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Tribological and scratch testing techniques were applied to metallurgical coke samples to determine (1) the abrasive strengths of the coke microtextural constituents, and (2) the strength of the interfaces between the inertinite maceral derived components (IMDC) and the reactive maceral derived components (RMDC), as a function of the properties of the parent coal(s). These parameters were quantified via the application of advanced microscopy techniques and then related to fundamental coal properties, including rank, measure, petrographic composition, and grind characteristics.

During tribological testing, a stationary pin or ball indenter is under a controlled load in contact with a rotating polished block of the material being tested. The wear track is then analysed to determine the degree and nature of the damage to the surface. The wear that occurs in rotational tribology tests is due to the progressive loss of surface material at the points at which the two surfaces (the polished block and the indenter) come into contact as they rub against each other. One of the key measurements that can be obtained from tribological testing is the coefficient of friction (COF). The frictional force between the polished coke block and the indenter shows their resistance to relative motion, and indicates the susceptibility of the coke to tribological wear. The higher the COF, the greater the efficiency in transferring mechanical energy to the coke that can weaken or break it up.

The strength attributes of cokes were related to coal properties, demonstrating that tribological and scratch testing techniques can be used to distinguish between cokes of different coal origin. The key findings were:

(1) IMDC abrasion is insensitive to parent coal rank. (2) RMDC abrasion is sensitive to parent coal rank. (3) RMDC fracture mechanisms are insensitive to parent coal petrographic composition. (4) Coal blending was found in most circumstances to produce stronger RMDC-IMDC interfaces than were obtained in the cokes formed from the constituent single coals.

The essential next step will be to use these findings to identify a path to help improve coke strength prediction and coke resistance to abrasion in the blast furnace. This would help to improve the accuracy of models used by the coal technical marketing industry to predict the value of their coal and coke products.

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## SIMULATION RESEARCH ON SPRAYING STEAM ON SINTERING BED SURFACE

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The process of spraying steam on surface of sintering bed was studied by using Fluent in this paper. The model was simplified into 2D and only front part of sinter machine was studied. As simulation results show that : (1) average temperature of sintering bed raised 20.3 [U+2103] and temperature of off-gas raised 35.42 [U+2103] after spraying steam; (2) the CO in off-gas became lower and CO<sub>2</sub> in off-gas getting higher when spraying steam and CO<sub>2</sub>/[U+FF08]CO+CO<sub>2</sub>[U+FF09] of off-gas raised 9.35% compared with spraying nothing; (3) hydrogen (0.14%) was found in off-gas when steam spray on sintering bed surface which means that water may have some reactions with carbon and (or) CO. Some industrial tests were taken after simulation. And the tests results show that sintering speed was accelerated and sinter qualities were improved and solid fuel consumption was reduced about 1.64kg/t by spraying 2t/h steam on sintering bed surface.

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## INCREASE IN PRODUCTION BY INCREASING DOUBLE TROUGH OPERATION THROUGH STRAIGHT CAMPAIGN OF TROUGH REPAIR AT G BLAST FURNACE, TATA STEEL JAMSHEDPUR

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Non-drainable trough repairs are inevitable in blast furnaces, limiting the drainage facilities. This issue became a bottleneck at G blast furnace leading to a reduction in the production levels. There are two drainable troughs at G Blast furnace with a campaign life of around 160ktons. Two types of repairs are carried out; minor repair after a life of 100ktons and major repair post the trough campaign life. The duration of trough minor repair is around 42 hours and that of trough major repair is around 85hours. As a result a total of 13 major and 13 minor repairs are carried out, thereby resulting in an annual production loss of 17,000 tons. Therefore, to reduce this production loss, various possibilities were explored to lower the frequency of trough repairs, without any compromise in trough health. The paper details out the process followed, resulting in increment in double trough operation by 13 %, which led to an increase in annual production by 17000 tons .Additionally it also helped to reduce specific trough refractory consumption by 13%.

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## OPTIMIZATION OF ROTATING CHUTE SHAPE IN BLAST FURNACE BASE ON DEM

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The chute shape determines the particle trajectory on and leaving the chute, and further affects the burden distribution in blast furnace. Therefore, a three dimensional model of the upper part of serial type bell-less top blast furnace is established based on discrete element method. The effects of chute shape and chute angle on the burden distribution on the chute and at the throat of blast furnace. The results show the main striking point is the largest for semicircle shape chute, followed by trapezoidal shape chute, and the smallest for rectangular shape chute. The burden weight maximum position is further than MSP position and the margin between them increases with the increase of chute angle. The burden thickness at blast furnace throat is the smallest at 20 ° chute angle for semicircle shape chute, and at 30 ° chute angle for rectangular shape chute, and at 40 ° chute angle for trapezoidal shape chute. Semicircle shape chute is beneficial to obtain uniform radial size distribution at 20 ° and 30 ° chute angle, while it is trapezoidal shape chute at 40 ° shape chute. Rectangular shape chute helps to form aggregated burden stream at different chute angles, which is beneficial for practical operation to perform precise burden control. Some optimizations of chute shape are also put forward to provide guidance for practical workers.

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## **A CLEANER AND EFFICIENT PROCESS TO PREPARE VANADIUM PENTOXIDE FROM THE CONVERTER VANADIUM SLAG**

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The converter vanadium slag is a byproduct of the iron making process when using the vanadium titanomagnetite as the iron raw material. A cleaner process including calcified roasting, dilute acid leaching, precipitation purification, vanadium precipitation with ammonium salt followed by pyrogenic decomposition was proposed to extract vanadium resource from this slag. And then vanadium pentoxide with purity over 98% was prepared, which can be used as additives for high strength low alloy steel production. A total vanadium recovery beyond 80% was achieved in this whole process. Since no sodium and potassium salt was introduced, waste water generated was closed-circulating after removing the enriched impurities of P, Si, Ti and Cr with adding powder CaO. The content of V<sub>2</sub>O<sub>5</sub> in residues after vanadium extraction was lower than 1.2wt.%, while other valuable metals like Fe, Mn, Cr and Ti were concentrated. With no alkaline metal salts added in this process, the metals of Fe, Mn, Cr and Ti in the residues were more likely to be recovered with conventional pyrometallurgy processes.

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## **IRON & STEEL-CHEMICAL COMBINED MAKING TECHNOLOGY –The Carbon Recycling and High-efficiency Utilization of Iron & Steel-Work Off-Gases**

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The iron & steel-work off-gases e.g. blast furnace gas(BFG), basic oxygen furnace gas(BOFG) and coke oven gas(COG) are generally used for heat or power generation, but the efficiency of gases utilization is low. A total solution using PU-1 molecuar sieve and vacuum pressure swing adsorption(VPSA) process, gains the carbon monoxide(CO) gas economically which purity can be more than 99%vol., let it be possible that produce chemical product by using the BFG, BOFG

or COG efficiently. This solution has been applied in two iron & steel enterprises in China, one is produce formic acid using BOFG, the other is produce ethylene glycol using BOFG and COG. Iron & steel-Chemical Combined Making Technology significantly increase the efficiency of gases utilization, reduce the CO<sub>2</sub> emissions, is one way of green development for iron & steel enterprises in the future.

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## **PREPARATION OF ZNO/ASC BY SOLVOTHERMAL AND ITS DESULPHURISATION PERFORMANCE**

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ZnO/activated semi-coke desulfurizer was synthesized using hydrothermal method. The obtained samples were characterized by X-ray diffraction, scanning electron microscopy, transmission electron microscopy and N<sub>2</sub> adsorption. The effects of the loading amounts of ZnO, reaction time and temperature on the performance of ZnO/activated semi-coke's desulfurization capability were investigated in a fixed-bed reactor. The results showed that the loaded substance on activated semi-coke is pure ZnO with flower-like nanostructures, and the optimum condition for preparing ZnO/semi-coke are as follows: the ratio of loading (mass ratio of ZnO to activated semi-coke) is 1:25, the hydrothermal reaction time is 12h, and the hydrothermal temperature is 150°C. The pore structure of the as-synthesized desulfurizer changes slightly before and after desulphurization, indicating that the pore structure of the carrier activated semi-coke is not damaged, which is beneficial to the regeneration of desulfurizer.

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## **THE PERFORMANCE AND APPLICATION OF CARBON BRICK IN BLAST FURNACE**

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In order to evaluate the performance of UCAR carbon brick in blast furnace, the production technology characteristics and the application of UCAR carbon brick in blast furnace were analyzed. Analytic hierarchy process was used to calculate the weight of the performance index for carbon brick, the erosion resistance of carbon brick in molten iron was considered as the key performance. The erosion resistance of UCAR carbon brick in molten iron was investigated through the experiments, carbon content in molten iron had a great influence on erosion.

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## **INFLUENCE OF CAO/SIO<sub>2</sub> AND MGO ON PROPERTIES OF BLAST FURNACE SLAG IN JISCO AND THERMODYNAMIC ANALYSIS**

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In order to clarify the impact mechanism of CaO/SiO<sub>2</sub> and MgO on the performance of Jiusteel blast furnace slag, based on the actual composition of Jiusteel blast furnace slag, the influences of CaO/SiO<sub>2</sub> and MgO on viscosity and melting temperature of slags were investigated. Furthermore, the activity, liquidus temperature, liquid region and phase change of slag from 1600 [U+2103] to 1000 [U+2103] were calculated by using Factsage thermodynamic software. Finally, based on the current raw material conditions in JISCO, the proper CaO/SiO<sub>2</sub> and MgO of slag in Jiusteel blast furnace was discussed.

**CO2 reduction and energy saving / 66**

## DEVELOPMENT OF ENERGY RECOVERY SYSTEM FOR FINEX®

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The energy recovery system for FINEX® has been developed and adopted with commercial scale to the No.3 FINEX® plant at POSCO's Pohang Works. The energy recovery system is composed of heat recovery steam generator, dry de-dusting, and expansion turbine-driven power generator, which are optimally configured with adjusting the balance between system efficiency and the process restrictions. For the reliable design, the each components has been selected among the best available technologies, and customized to the FINEX® process conditions through the pilot scale test.

The commercial operation of energy recovery system commenced from July 2017, and demonstrated the satisfactory performance as aimed. At present, the energy recovery system is being stably and reliably operated, and contributes to the cost and energy savings at No.3 FINEX® plant. This paper presents the development progress and operating status of energy recovery system tailored to the current FINEX® plant, and evaluates the change and enhancement in FINEX® process. Also, the further optimization is discussed for the proposal of more efficient and economical adoption to the next FINEX® plant.

**Blast furnace ironmaking / 67**

## PRACTICAL STUDY ON THE FLOWABILITY AND COMBUSTION CHARACTERISTICS OF PULVERIZED COAL FOR IMPROVING PCI OPERATION EFFICIENCY

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Pulverized Coal Injection (PCI) into the Blast Furnace (BF) is well-known process for cost saving of the BF. Most of the ironmaking companies are trying to enhance the amount of Pulverized Coal Ratio (PCR) for the purpose of cost reduction. Two key factors, flowability and combustibility, of pulverized coal should be estimated to achieve higher PCR under stable operation condition. The flowability, which depends on characteristic property of coals, influences the even distribution of coal injection across all tuyeres. For Hyundai steel PCI facility (PW type), the flowability of

pulverized coal plays more important role for stable injection due to dense phase transfer system. The combustibility also determines permeable and thermal conditions inside raceway through rapid reactions, combustion followed by volatilization. In this study, both of flowability and combustibility were estimated with a powder flow tester and a drop tube furnace, for measuring shear stress and burn-out of pulverized coal, respectively. 10 kinds of coal brands were analyzed to investigate the effect of coal properties, such as volatile matter, H/C ratio, ash composition, inertinite texture, and size distribution, on the two factors. Suitable ranges of those properties obtained from laboratory tests for stable and high efficiency of PCI operation were verified in long period practical operation in actual BF.

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## DEVELOPMENT OF NEW CHARGING TECHNIQUE FOR MIXING COKE IN ORE LAYER AT BLAST FURNACE WITH CENTER FEED TYPE BELL-LESS TOP

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Improved permeability and increased gas utilization have been desired in order to achieve low coke rate operation of blast furnaces. Coke mixed charging in the ore layer is one measure for realizing these improvements. A new charging technique for mixing nut coke in the ore layer at a blast furnace with a center feed type bell-less top was developed and investigated in an experiment with a 1/18.8 scale model of an actual blast furnace at JFE Steel. The discharge pattern of the mixed nut coke discharged from the bell-less top was improved, and the radial distribution of the mixed nut coke ratio at the furnace top after the mixed materials were charged in the blast furnace was also improved by the new charging technique in which nut coke was charged in the determined port of the upper bunker before ore was charged in the upper bunker. The new charging technique was applied to an actual blast furnace at JFE Steel, and improvement of gas permeability and a decrease in coke rate were confirmed.

**CO2 reduction and energy saving / 69**

## MAGNETITE REDUCTION by H<sub>2</sub> DURING MICROWAVE HEATING

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Recently, reduction of CO<sub>2</sub> emission and also energy conservation in ironmaking process are serious concerns which persuaded the researchers to look for a cleaner and a more efficient method for iron production. Microwave heating has been considered as a new heating method for iron ore reduction which could decrease the required carbonaceous materials for iron production. However, it would be preferable for low carbon ironmaking if reduction reaction could be conducted by non-carbonaceous materials, such as H<sub>2</sub>, during microwave heating. For this purpose, magnetite would be the best form of iron ore due to its high microwave susceptibility even at room temperature. In the present study, possibility of magnetite reduction by H<sub>2</sub> during microwave heating is investigated using a tablet shape magnetite sample and a microwave generator with a frequency of 2.45 GHz at the output power of 1050 W. The sample was heated to ca. 530°C in 6 minutes under N<sub>2</sub> atmosphere followed by changing the atmosphere from N<sub>2</sub> to H<sub>2</sub> and then heating for

a certain time. Results of the weight change measurements showed that a reduction degree of 8, 17.6, 30, 32, 36, 51 and 65% could be achieved after a treatment under H<sub>2</sub> for 2.5, 7.5, 11, 15, 20, 30 and 60 minutes, respectively. Reduction of magnetite to FeO and Fe seems to cause some variations in microwave absorption capability of the sample due to the different magnetic and dielectric properties of the new-formed phases. Also, some changes were observed in the heating pattern of the sample after changing the atmosphere to H<sub>2</sub> confirming the effect of the above-mentioned phase transformations on microwave absorption capability. Furthermore, according to SEM observations of microwave heated sample, some cracks were formed which would be due to the rapid and selective heating characteristics of the microwaves irradiation causing a favorable porous structure for the reduction.

#### Blast furnace ironmaking / 70

### EFFECT OF HYDROGEN CONCENTRATION IN BLAST FURNACE REDUCING GAS ON REDUCTION BEHAVIOR OF IRON ORE SINTER

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For decreasing CO<sub>2</sub> emission from iron making process, increasing hydrogen concentration in blast furnace is suitable method. However, the property of iron ore agglomerate such as reducibility should be optimized because hydrogen reduction is endothermic reaction and temperature distribution in BF drastically changes by increasing hydrogen concentration. In this study, the effect of hydrogen concentration on the reduction behavior of mineral phases in iron ore sinter is evaluated. Ten sinter samples which were produced by Japanese steel mill were used. The composition of the mineral phases in these samples was analyzed by XRD and image analysis. Sinter sample was reduced under the simulated conditions such as standard (N<sub>2</sub> - 48% (CO+CO<sub>2</sub>) - 5.8% (H<sub>2</sub>+H<sub>2</sub>O)) and high hydrogen (N<sub>2</sub> - 48% (CO+CO<sub>2</sub>) - 13% (H<sub>2</sub>+H<sub>2</sub>O)). After reduction, microstructure of the sample was observed. Sinter has components of hematite, magnetite, calcium ferrite and slag. Furthermore, calcium ferrite could be divided into four types which were acicular calcium ferrite with primary hematite (1H-ACF), columnar one with secondary hematite (2H-CF), small columnar one with magnetite, and large columnar one with magnetite. Increase in hydrogen concentration accelerates the reduction of hematite, 1H-ACF, and 2H-CF in all sinter samples while the reduction of magnetite, and calcium ferrite with magnetite is not done.

#### Blast furnace ironmaking / 71

### INFLUENCE OF CRYSTAL STRUCTURE AND CHEMICAL COMPOSITION OF SILICO-FERRITE OF CALCIUM AND ALUMINUM ON ITS REDUCIBILITY

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Silico-Ferrite of Calcium and Aluminum (multi-component CF) is one of main minerals in iron ore sinter. Multi-component CF is classified by columnar structure (SFCA) and acicular structure (SFCA-1), which have different crystal structures. It is considered that SFCA-1 has higher reducibility than SFCA, however, the results reported by previous studies have been included factors of adjacent structure such as pores and slag. Moreover, the influence of composition for reducibility has not been clarified while multi-component CF has wide chemical composition. In this study, influence of crystal structure and chemical composition for its own reducibility is investigated on silico-ferrite of calcium and aluminum. Commercial reagents were used to fabricate multi-component CF. Four different chemical composition powder mixtures of SFCA and SFCA-1 were prepared, respectively. These powder mixtures were heated at the range between 1200 and 1400°C, and quenched. Obtained SFCA and SFCA-1 samples were crashed to be powder samples.



These powder samples were heated in XRD chamber with heating unit up to 800°C. Atmosphere are N<sub>2</sub>-CO-CO<sub>2</sub> and including two different compositions of H<sub>2</sub>-H<sub>2</sub>O system. These atmospheres were changed to simulate blast furnace process. SFCA samples were not reduced until 800°C in CO-CO<sub>2</sub>, whereas the progress of reduction was shown in CO-CO<sub>2</sub>-H<sub>2</sub>-H<sub>2</sub>O atmosphere. SFCA-1 samples were reduced from 500°C in CO-CO<sub>2</sub> atmosphere. The reduction of SFCA and SFCA-1 are enhanced by high H<sub>2</sub>-H<sub>2</sub>O composition. Reducibility of SFCA is independent with Fe composition, whereas SFCA-1 is enhanced with increasing Fe composition. SFCA-1 on its reducibility is higher than SFCA. It implied that the valence on Fe is affect to its reducibility.

#### Cokemaking / 74

### EXPLORATION OF COAL FUSIBILITY IN THE COKE-MAKING PROCESS AND THE LINKS TO COKE QUALITY

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Despite the extensive research in the prediction of coke properties from the parent coals, at present, no single model exists to adequately predict coke quality from all coal basins. Whilst heavily used as a feature in early coke quality prediction models, the binding behaviour of the maceral components, termed fusibility, has had limited success in being implemented into a global prediction model. Part of the limitation of existing models is the arbitrarily assumed fixed proportion of fusing macerals within each coal, despite evidence suggesting that the behaviour of macerals varies by coal basin. Current methods of determining coal fusibility rely on manual point count methods on both the coal and coke structures, which is a costly process with significant measurement variability. This study developed a method of predicting the fusibility by using a data mining approach, applied to commonly measured coal quality parameters. The proposed method has implications for determining and interpreting the contributing factors to coal fusibility. Further, as implemented within a coke quality prediction model, this method contributes to the knowledge of the relationship between fusibility and coke quality parameters.

#### CO<sub>2</sub> reduction and energy saving / 75

### APPLIED FUNDAMENTAL RESEARCH OF FERRO-COKE PRODUCTION BY THE STAMPED CHARGING COKE-MAKING PROCESS

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Ferro-coke is a highly reactive coke and considered a promising advanced burden material for blast furnace ironmaking due to a potential of decreasing RAR and CO<sub>2</sub> emission. The essential reason is it reacts with CO<sub>2</sub> in BF gases at lower temperatures, which is resulted in by the catalytic effect of metallic iron, and leads to a lower temperature of the thermal reserve zone. However, since iron ores are an inertial material, the mechanical strength of ferro-coke is commonly inferior to the coke prepared without iron ore addition. This violates the requirement for coke in providing mechanical support to the large charge column and in permitting the gases to ascend

through the voids. In this work, focused on ferro-coke, a great effort has been made to clarify the influencing factors of reactivity as well as mechanical strength at the room temperature as well higher temperatures after reaction and to determine the quantitative relationship between the quality indices and the productive parameters. Two processes can be applied in the production of ferro-coke, i.e. the traditional battery cokemaking process and the briquetting/shaft process. The briquetting/shaft furnace process is superior to the former in higher iron ores blending ratio, and the traditional battery cokemaking process is superior to the later in higher process maturity, higher production capacity, no need in binders. For this reason, the traditional battery cokemaking process was selected for the preparation of ferro-coke. Further, the stamped coke battery route was tried in this study in order to obtain ferro-coke products with higher mechanical strengths at a same blend ratio of high quality cokemaking coals. It was revealed by this work that the main factors influencing on the reactivity (also the starting gasification temperature) and mechanical strength of ferro-coke are the coking capacity (Vadf, G and Y values) of coal blend, the quality (gangue materials content, combined water content, size distribution) and blend ratio of iron ores, carbonization conditions (heating speed, carbonizing temperature, soaking time, etc.), and the bulk density of coal charge in particular. A mathematical model has been built up based on the results of a systematical experimental study. This model can be used either for forecasting the reactivity and mechanical strength of ferro-coke under a specified production condition, or for determining the productive conditions for achieving a specified quality standard of ferro-coke. In the 6 kg experimental coke oven of Wuhan University of Science and Technology, a ferro-coke sample with quality indices that are comparable to the industrial coke fed into 2300 m<sup>3</sup> BF has been produced; its declining rate of mechanical strength with the reactivity increasing is as small as that of the formed ferro-coke sample prepared in laboratory by the hot-briquetting/shaft process.

**Direct reduction / 76**

## SEARCH FOR AN ALTERNATIVE PROCESSING OF MAGNETITE CONCENTRATE CONTAINING OXIDES OF VANADIUM AND TITANIUM

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**Abstract** An existing scheme of vanadium production from low-titanium magnetite concentrates is energy-consuming and associated with loss of valuable elements, e.g. titanium. The present work investigates the possibility of obtaining products, which are different from the processing using the conventional technological scheme, for further development of an energy-efficient and wasteless technology. A magnetite concentrate containing titanium and vanadium oxides was reduced with coal in a vertical furnace. The effect of temperature was studied at 1000, 1100 and 1200 oC. After reduction the metallized product was melted to separate metallic Fe from slag containing V<sub>2</sub>O<sub>5</sub> and TiO<sub>2</sub>. The phases obtained during reduction and smelting were studied using XRD and SEM analysis. The concentration of V<sub>2</sub>O<sub>5</sub> and TiO<sub>2</sub> in a final product has increased in comparison with the initial magnetite concentrate with minimum transfer to metal. **Keywords:** magnetite coal reduction, vanadium oxide, titanium oxide.

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## SIMULATION OF BLAST FURNACE HEARTH AND BOTTOM EROSION

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The state of blast furnace (BF) campaign life and the erosion mechanism of BF hearth and bottom are summarized. According to the design and erosion conditions of hearth and bottom of a blast furnace with effective volume of 3200m<sup>3</sup>, a two-dimensional mathematical model was developed using the theory of heat transfer with ANSYS to monitor the erosion state of blast furnace's hearth and bottom. The temperature field distribution of hearth and bottom was obtained at different stages of service, including the early state, the middle state, the mid to late state and the late state. The calculated erosion graph indicates that erosion line at 1150 [U+2103] was located under the iron notch and at the corner of the hearth and bottom, and the "elephant foot wear" was not obvious. Compare with the different situation of the temperature distribution and the location of the erosion line at 1150 [U+2103] of the hearth and bottom at different BF service period, the reason for the change were analyzed, and the influencing factors for hearth lining temperature were discussed.

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## **BLAST FURNACES CAMPAIGN EXTENSION AND RE-LINE PLANNING AT CHERMK – SEVERSTAL**

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Intensive operation of blast furnace allows increase in production of hot metal. However, furnace life could be sacrificed. CherMK and Hatch systematically monitor conditions of BF lining using Acousto Ultrasonic-Echo (AU-E) non-destructive methodology. Testing of blast furnaces revealed problematic areas with refractory deterioration, formation of elephant foot, extent of accretion and rate of refractory wear, cracks and anomalies. Improvement in coke quality, periodical staves washing, addition of titania, grouting etc. were recommended and implemented to prolong furnace life while maintaining the intensity of furnace operation. Comparison of NDT results and physical measurements showed that they are in a good agreement. Estimated rate of refractory wear allowed to predict the remaining campaign of the blast furnace and start preparation for furnace shutdown and modernization.

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## **REGULARITIES OF HIGH INTENSIVE BLAST FURNACE OPERATION**

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The influence of the melting intensity, which is defined and estimated as a specific blast-furnace productivity, on the stability of blast furnace operation and conditions of indirect reduction of wustite is evaluated and studied. It is shown that at elevated melting intensity -specific productivity the incremental change in the melting intensity leads to a more modest variation in

the efficiency of CO utilization. The increase in the stability of the processes in the wustite indirect reduction zone is accompanied by a decrease in the fluctuation of the chemical composition of the hot metal and slag. The theoretical calculations and production data analysis revealed that the higher intensity of blast furnace process leads to more stable furnace' thermal conditions. This is confirmed by operating data of blast furnaces at NLMK-Russia.

## Pelletising / 81

### COMPARISON OF PELLETIZING TECHNOLOGIES

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The straight grate and grate kiln indurating processes are the two proven and widely accepted iron ore pelletizing technologies. Hatch performed a technical and economic comparison between the two processes, emphasizing their specific advantages and applicability for selected regional conditions. The technology comparison is based on publicly available literature and our extensive database of iron ore pelletizing operations. Included in the comparison are straight grate and grate kiln plants supplied by long established original equipment manufacturers, as well as grate kiln plants supplied by Chinese equipment manufacturers. A special emphasis is given to limonitic ores, since much growth in pelletizing capacity is expected to occur in coming years for processing of these ores. Advantages and disadvantages of each technology are evaluated. The straight grate and grate kiln technologies are comparable and completely applicable for processing of Indian hematite and limonitic ores. The Chinese grate kiln technology is best applied for smaller capacity pelletizing plants and is less efficient.

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### REGULARITIES OF HEAT EXCHANGE AT MODERN CONDITIONS OF INTENSIVE BLAST FURNACE OPERATION

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Changes in heat transfer regularities of blast furnace process in course of this process refinement are considered and evaluated. It is shown that stable and profitable operation of modern intensive blast furnace process with variety of raw materials, combined blast etc. could be achieved only preserving two distinct zones of high intensive heat transfer. Any changes in melting process do not change this fundamental characteristic of blast furnace process. Heat exchange processes in the upper and bottom stages of blast furnace are not completely autonomous since both depends on extend of direct reduction process. Experimental and theoretical investigation of blast furnace process in modern conditions showed the existence of two zones of delayed heat exchange. The upper delayed heat exchange zone is characterized also as delayed mass exchange zone. Therefore, this volume of blast furnace from the heat transfer point of view could be considered as a reserve zone of blast furnace. In the lower zone of delayed heat exchange processes the speed of chemical reactions is comparatively high. Therefore, this zone cannot be considered as a part of reserve zone. From the point of view of heat exchange processes assessment and blast furnace control in modern conditions the furnace still has to be divided by two heat exchange zones – upper and bottom. The boundary between these zones is located at the upper levels of mixed reduction of iron oxide, between elevation of the beginning of carbon gasification reaction and the level, below which reduction of iron oxides characterized only by direct reduction.

**Modelling and simulation in coke and ironmaking / 83**

**MODELLING OF GAS AND MATERIAL DISTRIBUTION, RACEWAY CONDITIONS AND SLAG MODE OF OPERATION OF BLAST FURNACE**

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Any expert system of blast furnace should include the following models: the model to estimate material and gas distribution and their temperatures at the furnace top based on measurements by radioisotope profile scanner (or other type) and industrial IR-camera; conditions and dimensions of the furnace raceway; slag model which allow estimate the viscosity of primary, intermediate and final slags of blast furnace process. Practical realization of these models allows to prolong life of refractory lining, staves and tuyeres, increase in blast furnace productivity and reduction in production cost of hot metal. Reliability of Expert system instrumentation and accuracy of measured data during the long service time of expert system in blast furnace operating environment also discussed in the paper. Case studies of such systems operation are presented for blast furnace #3 at Tulachermet and blast furnace #5 at CherMK-Severstal, Russia for several years of their operation.

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**THE APPLICATION PRACTICE OF PROLONGING SERVICE LIFE OF LARGE SIZE BF COPPER COOLING STAVE**

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The damage of copper cooling stave in several china's blast furnace is investigated. Furthermore, the damage mechanism has also been analyzed. It's shows that the breakage of copper cooling stave mainly due to unstable slag skull and frequent wearing by furnace burden and gas flow, as well as improper design. Based on which some measures were suggested for prolonging the service life of copper cooling stave. Such as controlling the oxygen content of the copper cooling stave body, ensuring reliability of BF cooling system and maintaining appropriate peripheral gas flow. Most of all, the author believes that long service life of BF copper cooling stave can be achieved by appropriately controlling of peripheral gas flow intensity, protecting the slag skull from frequent peel-off and reducing the thermal shock. Additionally, the operation practice of No.1 BF of Shougang corporation proves that timely spray-lining is effective for handing damage copper stave, Its copper cooling stave life has been more than 13 years. At last, it is pointed out that appropriate use of copper cooling stave can effectively extend the service life of blast furnace.

**Blast furnace ironmaking / 86**

**APPARENT SOFTENING VISCOSITY MEASUREMENT OF GRANULATED SLAG PACKED BED WITH SOFTENING AND MELTING SIMULATOR**

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Low carbon operation of blast furnace is important technology for mitigation of CO<sub>2</sub> emission from ironmaking process. This operation means decreasing of coke rate in raw material charging amount into blast furnace. This situation makes severe condition of gas permeability in especially cohesive zone of blast furnace. Therefore, cohesive zone formation behavior should be correctly understood. In this study, slag is focused as the most important melt in cohesive zone because they have higher viscosity and possibility to clogging than molten iron. Using the newly developed softening and melting simulator, effect of the slag behavior in softening and melting process on gas permeability through granulated slag packed sample layer was investigated. In order to evaluate softening behavior of sample packed bed, an apparent softening viscosity is applied. The apparent softening viscosity is estimated from shrinkage resistance of the sample packed bed from 1200-degree C to 1500-degree C under 0.1 MPa load. The slag samples were synthesized in gradual cooling condition to avoid making glassy slag. The slags were crushed and sieved in 4-5mm and then charged into graphite crucible, inner diameter 35 mm, which has holes in bottom. The sample was heated up to 1200-degree C with 1000-degree C/min. After reaching 1200 degree-C, heating rate was changed to 10-degree C/min. During heating experiment, 0.1 MPa load was added to the sample layer from top part through lid and N<sub>2</sub> gas was flowed from bottom side with 1NL/min. Displacement amount of the sample layer thickness and gas pressure drop were measured for evaluation of softening and melting behavior. From this evaluation, it was found that the apparent softening viscosity at higher shrinkage degree is strongly related with pressure drop in the sample packed bed and surface tension of molten slag has dominant effect on the apparent softening viscosity.

**Sintering / 87**

## DEVELOPMENT OF A TECHNIQUE THAT ADDING IRON ORE MICRO-PARTICLE BINDER GROUND BY VERTICAL WET BALL MILL FOR INCREASE OF IRON CONCENTRATE AT SINTERING PROCESS

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In order to decrease Reducing Agent Rate (RAR) and CO<sub>2</sub> emission of blast furnaces, it is important to decrease slag volume. In NSSMC, more than 70% of blast furnace burden is sinter ore, so slag volume control is very important. However slag contents of sinter feeds are increasing because of resource deterioration. Therefore, using high amount of iron ore concentrate, which has relatively lower slag contents, is desired. Nevertheless, it causes decreasing of the permeability of the sintering bed and sinter productivity. In order to increase the amount of concentrate, NSSMC has developed the new technique adding micro-particles for binder. In this report, vertical wet ball mill was installed on sub granulation line of Wakayama No.5 sinter plant. In this line, about 0.4% of Australian pisolite ore was ground to -10 micron > 60% and added into intensive mixer with iron concentrate and other sinter feeds. After mixing, they were granulated by a pan-pelletizer. After that, they were charged into sinter machine with other materials granulated in main granulation line with two drum mixers. It was confirmed that up to 13.5wt% of concentrate can be used without decreasing of sinter productivity by adding micro-particles.

**Sintering / 88**

## ASSIMILATION BEHAVIOR OF MgO SOURCE DURING IRON ORE SINTERING

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Improvement of sinter reducibility is necessary for high production rate of blast furnace, involving reduction of the slag component in the sinter. Replacement of peridotite (MgO-SiO<sub>2</sub>) for dolomite (CaMg(CO<sub>3</sub>)<sub>2</sub>) is a potent option as dolomite does not contain SiO<sub>2</sub>. However, dolomite is hard to assimilate and deteriorates sinter strength. In this study, assimilation behavior of dolomite has been investigated by means of tablet firing experiments in an electric furnace, where the tablets was compacted with a 2-3mm(?) dolomite particle in the matrix of calcium ferrite reagent. As a result, a reaction layer of a dolomite particle and calcium ferrite was formed by 20μm thickness at 1473K which is the initial melt forming temperature and identified as SFCA by EPMA. At 1527K, the reaction layer thickened to 500μm.

Postersession and Coffee Break / 89

## MODEL FOR EMISSION REDUCTION OPTIMIZATION OF IRONMAKING PROCESS IN BLAST FURNACE

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Blast furnace emission reduction optimization model is based on substance conservation and energy conservation of ironmaking process. The mathematical model is established using the multiple-objective optimization method with the cost and CO<sub>2</sub> emission taken as objective functions. The optimization variables and constraints are determined by the characteristics of blast furnace ironmaking process and the objective functions. The optimized results are obtained by using the GRG (Generalized Reduced Gradient) nonlinear solving method. Then, the model is applied to the B# blast furnace in Bayi Steel in China. By comparing the optimized results with the actual production data, the model is verified correct. Meanwhile, the model is applied to analyze the effects of coke ratio, coal ratio, blast temperature and other factors on the cost and CO<sub>2</sub> emission. Then, some measures to cost saving and emission reducing have been proposed.

Smelting reduction / 90

## STATIC MODEL STUDY OF THE EFFECT OF DIRECT REDUCTION DEGREE IN COREX PROCESS

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Direct reduction degree in COREX affects the reducing gas component and effective heat utilization rate. The present work systematically studies the influence of direct reduction degree on these

characteristics in COREX through a static model. The model is developed based on mass and heat balances, which can calculate the consumption of iron ores, coal, fluxes, the volume and composition of the slag and the volume and composition of the reducing gas from melter-gasifier. The model is firstly validated by means of comparing calculated values with actual values. Then, the changes of heat flows, volume and component of reducing gas, and effective heat utilization rate in COREX induced by the variation of direct reduction degree are investigated. Finally, the suitable direct reduction degree in COREX is discussed. The findings of this work should be useful for control and optimizing of COREX operation.

#### Blast furnace ironmaking / 92

### EVALUATION ON DECHLORINATION EFFECT FOR ALKALI LIQUOR SPRAY SCRUBBER AFTER BF DRY DUST-CATCH

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In recent years, dry de-dusting technology has been widely used. Alkali liquor spray scrubber was added after dry dust-catch process to removal such the corrosive medium as chlorine. However, the problem of corrosion cracking often occurred in the gas and hot blast pipes. The evaluating method was present through directly measuring the chlorine content in gas before and after alkali liquor spray scrubber. Compared to control PH value in alkali lye, the method above mentioned is more direct and reliable. The results show that the removal rate of chlorine in gas is between 10%~70%, and there is still the risk of corrosion of the equipment in the downstream process.

#### Sintering / 93

### NUMERICAL SIMULATION OF HEAT TRANSFER INSIDE THE SINTERING BED BY EMPLOYING DIFFERENT CROSS-SECTION SHAPES

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Thick bed technique has been widely used in the sintering plants, because it can save fuel consumption and achieve significant economic benefits. However, when the sintering bed height further increases, the cross-section shape would vary with respect to the inclination angle, and directly affect heat transfer inside sintering bed afterwards. After a two-dimensions(2D) mathematical model is established and validated against the sintering pot test measurements, present work designs four inclination angles, namely 9°, 18°, 26.6°, and 33.7°, in order to investigate the effects of cross-section shapes on heat transfer during the sintering process. The results show that the trapezoid-liked shape of sintering bed cross-section leads to the non-uniform temperature distribution in the width direction, where the temperature close wall is higher than that in the center. Although the increases on the inclination angles from 9° to 33.7° gradually decreases the sinter bed height with the same yield, the temperature difference between wall and center regions increases from 116 K to as great as 292 K.

Key words: sintering; cross-section shape; inclination angle; heat transfer; CFD

#### Postersession and Coffee Break / 98

### DETAILED DEM-SPH SIMULATION OF MELT PASSING PHENOMENA IN VARIOUS COKE BEDS



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A state-of-the-art numerical model was developed for analyzing packed bed structures containing non-spherical solids such as cokes and the high-temperature melt trickle flow characteristics of such beds. This enables the direct 3-dimensional analysis of packed beds that are difficult to visualize in experimental tests. The advanced discrete element method with 3D scanning technology is employed as a highly-accurate method for solid-particle motion simulation. It is a method using a contact force model that is expanded to capture the motion of 3-dimensionally freely shaped rigid bodies. Meanwhile, the sophisticated smoothed particle hydrodynamics method can track the motion of liquids without discriminating between continuous and dispersed phases. We used the boundary for the packed bed configured with non-spherical solids to carry out gas-liquid-solid 3-phase dynamic simulation. Based on this model, we carried out the large-scale simulations, and perform case studies and other studies of statistical processing, and investigate the effects of both physical properties and packed bed formed from various types of non-spherical cokes. Even for cokes bed of equal volume, different shapes changed the molten slag passage characteristics and static hold-up amount. Since the size of the hold up site is also influenced by the shape of the void at the top of the neck, the flow characteristics on the upstream side of the packed bed can also have a large influence. And we investigated the influence of melt physical properties on trickle flow, and clarified that an increase in viscosity increases holdup because limiting the effective flow path and suppressing the dispersion of the droplets promoted the enlargement of each stagnant droplet.

**Postersession and Coffee Break / 100**

## **INFLUENCE OF THERMODYNAMIC MELT FORMATION CHARACTERISTICS ON LIQUID PHASE FLUIDITY OF IRON ORE IN SINTERING PROCESS**

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The liquid phase fluidity of iron ore is one of the vital index of sintering characteristic, as the suitable melt fluidity can get a stronger bonding strength of sintered body. In this paper, FactSage thermodynamic calculation software and visible micro-sintering test device were conducted to research liquid phase fluidity and the main influence factors of melt formation characteristics. The results show that the rule of liquid phase fluidity of iron ore is obviously different when the flux is fixed with CaO ratio or fixed alkalinity. The generated liquid content of iron ore powder is the most important melt formation characteristic factor which affects its liquid phase fluidity. The higher the generated liquid content, the greater the liquid phase fluidity index. The content of gangue minerals affect the liquid phase fluidity of iron ore. The liquid fluidity index decreases greatly with increasing SiO<sub>2</sub> content results in lower generated liquid content and the liquid phase viscosity is increased. In contrast, with an increase in the Al<sub>2</sub>O<sub>3</sub> content only slightly increasing the liquid fluidity index.

**Blast furnace ironmaking / 101**

## **A study on the control of porosity and its reduction behavior by using FeCl<sub>2</sub> in FeO**

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The Influence of pore on reduction behavior of iron oxide is very important. The pore affects the reduction gas diffusion and thus the reduction behavior is affected. However, in most studies, porosity was used only as a tool for the resultant interpretation of the reduction. There is insufficient studies to identify porosity by artificially changing pore. In this study, we investigate the reduction behavior by changing only pores after fixing other influencing reducing factors.

FeCl<sub>2</sub> of high vapor pressure at high temperature, was used to control pores in the sample. FeO and FeCl<sub>2</sub> were physically mixed in a vertical furnace and the FeCl<sub>2</sub> was evaporated at high temperature to form pores. Reduction behavior was investigated by TGA experiment method. By using XRD, SEM, CIC, and BET analysis, the following results were obtained by examining the correlations of compositional equilibrium, morphology, Cl content, porosity and so on.

As expected, the amount of pores in the sample was increased in proportion to the amount of FeCl<sub>2</sub> initially added by evaporation of FeCl<sub>2</sub>. The amount of pores in the sample was increased, but the initial rate of reduction was inversely proportional to the pore volume. After the mid-reduction, the rate of reduction tended to increase again in proportion to the initial value of the sample. It was found that not only the amount of pores but also the quality of pores could be an important factor in reduction.

**Environmental control in coke and ironmaking / 102**

## MIGRATION OF ORGANIC SULFUR IN NANTONG AND LAIGANG COAL WITH ADDITION OF NaOH-H<sub>2</sub>O<sub>2</sub> UNDER MICROWAVE TREATMENT

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Nantong coal (NTC) and Laigang coal (LGC), the two typical high-sulfur coking coal in China, were investigated on their desulfurization processes with the addition of NaOH-H<sub>2</sub>O<sub>2</sub> under microwave treatment. X-ray diffraction (XRD), inductively coupled plasma (ICP) and fourier transform infrared (FT-IR) were performed to unravel the migration of organic sulfur in the two coal. In addition, the constituents of organic sulfur and content of functional groups in both two coal were also analyzed. NTC and LGC, with the addition of NaOH/H<sub>2</sub>O<sub>2</sub> at a volume ratio of 1:4 and microwaved at 1000 W for 10 min presented the highest desulfurization rates, that is, 22.3 and 31.75 % respectively. XRD analysis revealed that organic sulfur in the two coal was transformed into inorganic sulfur with the existence of sulfate or FeS, this transformation process inhibited desulfurization rate of the two coal. FT-IR measurement depicted that NaOH/H<sub>2</sub>O<sub>2</sub> ratio below and above 1:4 promoted and inhibited the desulfurization rate of the two coal. Moreover, the three sulfur-bearing functional groups were reserved in the two coal with the order of S=O > -S-H- > -S-S- under the NaOH/H<sub>2</sub>O<sub>2</sub> ratio of 1: 4, therefore, controlling of S=O in NTC and LGC is the key to improve the desulfurization rate.

**Pelletising / 103**

## RESEARCH ON PELLETS PROPERTIES PREPARED WITH DIFFERENT FINENESS FORSTERITE

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Basic characteristics of forsterite were systematically studied by chemical analysis, XRD, SEM-EDS. A series of experiments were performed to investigate the effect of forsterite fineness on pellets strength and porosity by changing pre-grinding time of olivine. It could be found that prolong the pre-treatment time of forsterite is beneficial to the promotion of pellets strength; there are two kinds of pores in the roasted pellets, which are large circular pores and intergranular pores. With the increase of the pre-grinding time, the shape and distribution of large circular pores become uniform, pore size and quantity of intergranular pores become small, thus pellets compressive strength increases firstly and then decreases slowly, porosity changes in the opposite direction. Optimal pre-grinding time of forsterite is 40~60min, under which condition could the pellets meet requirements of actual production.

**Blast furnace ironmaking / 107**

## FORMULATION OF SHRINKING BEHAVIOR OF SINTER DURING SOFTENING PROCESS

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In order to formulate shrinkage behavior of sinter during softening process, the effects of load and reducing gas composition on the shrinkage rate of sinter packed bed has been investigated using a softening-melting furnace. As a result, the shrinkage rate increased with increasing the load on the packed bed in temperature range from 1000 to 1200 °C, and decreased with increasing the reduction degree of sinter in temperature range from 1200 to 1300 °C. The results indicate that shrinkage mechanisms vary depending on temperature. In this study, softening process of sinter was formulated by dividing into two temperature regions. In the region I, the shrinkage rate increased in proportional to the impressed load, and was in inversely proportional to the softening viscosity. In the region II, the shrinkage rate increased in proportion to the generation rate of melt, and decreased with increasing the volume percent of metallic iron in the packed bed. The shrinkage in region II was inhibited with increasing the reduction degree of sinter since formed metallic iron served in the role of aggregate. The shrinkage rate of each region was expressed as functions of initial composition of sinter, load, temperature, and reduction degree. The calculated values were in good agreement with the experimental ones.

**Direct reduction / 109**

## KINETIC ANALYSIS OF CARBON FIBER DEPOSITION ON CATALYST IRON IN CO-H<sub>2</sub> MIXTURE GAS

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CO-H<sub>2</sub> mixture gas is often used for gas-based DRI process where carbon deposition reaction and Fe<sub>3</sub>C metal dusting play serious roles for a stable reduction operation. Fe<sub>3</sub>C decomposition leads to the formation of iron particles which is a catalyst for carbon fiber deposition. Because of the parallel occurrence of these reactions, kinetic analysis of them would be complicated. In the present study, to simplify the kinetic analysis, quantitative analysis was conducted by focusing on carbon fiber deposition using thermobalance. A powdery iron sample was prepared by reduction of Fe<sub>2</sub>O<sub>3</sub> at 600 [U+2103] in 100vol%H<sub>2</sub>. Carbon deposition on the iron sample

was investigated at 500, 600 and 700 [U+2103] under flowing 100%CO, 90vol%CO-10vol%H<sub>2</sub>, 75vol%CO-25vol%H<sub>2</sub>, 50vol%CO-50vol%H<sub>2</sub>, 25vol%CO-75vol%H<sub>2</sub> and 10vol%CO-90vol%H<sub>2</sub> mixture gases. Results showed that amount of the deposited carbon in the CO-H<sub>2</sub> mixture gas is larger than that in the pure CO gas. The largest amount of deposited carbon was obtained at 600 [U+2103] in the 75vol%CO-25vol%H<sub>2</sub> mixture gas. According to SEM observations and weight change measurements, carbon was deposited in fiber shape on the iron surface and amount of it was increased linearly with an increase in samples' weight change. The rate constant of Carbon fiber deposition was calculated considering Rideal mechanism with focusing on elementary reaction steps. It was found that the rate constant of the hydrogen-oxygen reaction step was the largest indicating a significant effect of hydrogen on promoting carbon deposition. This would be due to the removing oxygen from CO by hydrogen on the iron catalyst.

#### Recycling of in-plant residues / 110

### CASE STUDY OF RECLAIMING ZINC CONTAINING SLUDGE FROM SETTLING PONDS

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At SSAB Europe's integrated steel plant in Luleå, Sweden, much effort is directed towards maximising the recycling of in-plant residues. As the blast furnace (BF) operates with a 100 % pellet burden, the main part of all dusts and sludge are recycled via a BF cold bonded briquette and by the BF-injection of its flue dust. However, BF sludge is not presently recycled due to concerns regarding BF zinc load. This has continuously risen with increased recycling, to a current level of 100-120 g/tHM. In order to investigate the possibilities to introduce the recycling of all or parts of the freshly generated BF sludge ([U+F07E]0.8% Zn), or reclaiming previous year's produced BF sludge from settling ponds (0.2-0.5% Zn), a system analysis case study has been performed. The main focus of the case study was to estimate the capacity and economic benefits for BF sludge recycling (back to the BF) via the by-product briquette, based on a set maximum allowed blast furnace zinc load. An increase of the BF zinc load will, of course, raise the zinc level in the total system. Therefore, the developed system analysis tool used in this case study models the influence of the total BF zinc load on all generated residues and, hence, on the zinc content of recycled briquettes and injected flue dust. The establishment of the system zinc balance has been made possible due to good in-plant knowledge of zinc content in input as well as output materials. The system analysis shows that, with a maximum allowed BF Zn-load of 150 g/tHM, a "closed loop" recycling of freshly generated BF sludge is limited to about 40% (or 2 of 5 kg/tHM produced). However, in the case of reclaiming BF sludge from settling ponds the amount of recycled sludge can be considerably larger as the Zn content of recycled sludge will not be affected by the obtained increase in Zn content in the freshly produced BF sludge. At a Zn content of 0.4%, the amount of reclaimed sludge that can be recycled will equal the generated amount (i.e., about 5 kg/tHM). This will result in a reduced need for iron ore pellet and coke (dependent on the sludge Fe and C content) of some 2 kg/tHM, respectively. Hence, recycling of reclaimed BF sludge should be preferred to a "closed loop" recycling. A prerequisite for optimising the recycling of reclaimed sludge is to perform a comprehensive mapping of the zinc distribution in settling ponds.

#### Modelling and simulation in coke and ironmaking / 111

### Multiphase modelling of the blast furnace hearth during tapping

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The campaign length of a blast furnace is limited by the hearth inner lining lifetime. In order to maximize the campaign length and ensure a good draining of hot metal and slag, a good understanding of the flow in the hearth is essential. Challenges in modeling the flow involve several continuous phases (hot metal, slag and hot blast) as well as the presence of the deadman, a dense bed of coke particles. The shape and position of the deadman is highly dynamic and depend on several conditions, e.g. the weight of the burden, the deadman porosity as well as the liquid iron and slag levels in the hearth.

We present a numerical coupled CFD (Computational Fluid Dynamics) – DEM (Discrete Element Method) model to account for the transient behavior of the deadman. A VOF (Volume of Fluid) method is used to model the multiple continuous phases and the DEM method to model the discrete particles. The VOF and DEM models are coupled together in a 2-way manner, resulting in a complete 4-way coupled CFD-DEM model. Experimental validation was performed on a lab-scale particle filled tank and a demonstration of a small-scale blast furnace hearth is shown. Finally, we present our latest advancements towards modeling industrial scale blast furnaces. Due to the big dimensions, difficulties with long computational times arise as the particle number becomes infeasible. Commonly a parcel approach (coarse graining) is used to handle this problem, where several particles are treated as one large particle. However, in combination with VOF, the amount of coarse graining is limited as the increased particle size impairs the resolution of the fluid interfaces. Additionally, the wide range of time scales (ranging from particle collisions of fractions of a second to several hours of operational times) present in the blast furnace remains a major challenge. With information gathered from several short-term coarse grained DEM simulations for various liquid levels, we performed a long-term fully Eulerian simulation that used the data to create a dynamic porosity field. By not resolving any particle collisions in the long term simulation, we could simulate a longer process time while still accounting for the dynamic behavior of the deadman.

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## **A SUCCESSFUL ENDEAVOR IN DEVELOPING LONG LIFE TUYERE AT 'I'BLAST FURNACE, TATA STEEL, JAMSHEDPUR**

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Tuyere is the equipment which is supposed to sustain one of the most adverse conditions inside the Blast Furnace. Reliability of Tuyere is very important for trouble free safe operation of Blast furnace. Failure of tuyere increases cost of operation in terms of increased fuel rate and production loss as well as create hazard for the process and human. In front of the tuyere almost 2200 – 2300 degree centigrade temperature persists and at the same time tuyere is also subjected to mechanical abrasion from the descending materials. Till now there is no material developed for tuyere which can sustain such adverse conditions. Copper is used to exploit its high conductivity to sustain extreme temperature but it doesn't have abrasion resistance. Thus in almost in all Blast Furnaces of the world, different protective layers have been applied to improve the abrasion resistance but have achieve very limited success. 'I' Blast furnace was also struggling to achieve high tuyere life. Untimely, sudden and frequent failure of Tuyeres was posing serious threat in achieving stable and safe Blast Furnace operation. It was not only causing high copper loss, at the same time it was responsible for other associated problems like high fuel rate, loss of production etc. Apart from predictive modeling to avoid failure at odd hours, other steps were also taken like indigenous development of coating for top surface, measures to reduce heat loss from the inner surface, change in internal and external cooling circuit of tuyere and measures to prolong

life even after burning of the tuyere. This paper deals with all scientific and practical measures taken 'I' Blast furnace which aided to achieve a standard tuyere life.

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## EVOLUTION OF COKE NANOSTRUCTURE DURING GASIFICATION

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Coke reactivity is one of the most important parameters that defines coke quality. Although coal parameters such as coal rank, maceral composition and ash chemistry are used as indicators of coke reactivity, they cannot fully predict it. It is well recognized that reactivity of coke is controlled by catalytic mineral matter and its porosity, particularly its nanoporosity (pores of nm in size). Our previous studies on coke gasification under chemically controlled conditions concluded that catalytic mineral matter plays a dominant role on the reaction rate at initial stages whereas nanoporosity controls the reaction rate at the later stages. Porosity in cokes consists of open and closed pores. Recently we found that closed nanoporosity occurs in large proportions in cokes, almost all pores less than 5 nm are closed, and the amount of closed porosity in cokes was influenced by the maceral composition of the parent coals. In this study we examined how the fraction of the closed pores in cokes (as a function of pore size) changes during gasification under chemically controlled conditions. The cokes along with cokes prepared from maceral concentrates have been reacted with CO<sub>2</sub> to different burn-outs, namely 25%, 50% and 75%, using a fixed-bed reactor where the reaction is chemically controlled. The analysis of closed and open porosity in unreacted and reacted cokes was performed using Small Angle Neutron Scattering (SANS). Here we show that closed porosity down to sizes as small as 10 nm open gradually during gasification. Increased pore accessibility rather than pore growth may be the reason surface area of coke increases during the early stages of gasification. The influence of coal maceral composition and coal rank on pore opening in the product coke will be discussed.

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## A Thermodynamic Study on the Selective Reduction of Ni in NiFe<sub>2</sub>O<sub>4</sub>

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Limonitic laterite is an iron ore consisting of a mixture of hydrated iron oxide-hydroxides in varying composition. The generic formula of limonitic laterite is expressed as (Fe, Ni, Mg)O•(OH)•H<sub>2</sub>O. It is possible to obtain high quality ferronickel and iron oxide, which can be used as a blast furnace charge, through selective reduction of Ni using reduction potential difference between Fe and Ni in limonitic laterite. It is reported that the improvement of the quality of ferronickel and iron oxide extracted from limonitic laterite is controlled by optimization of the selective reduction of Ni in NiFe<sub>2</sub>O<sub>4</sub> mineral formed during calcination. In this study, the optimized reduction condition for the selective reduction of Ni in NiFe<sub>2</sub>O<sub>4</sub> is thermodynamically derived, and the effect of oxygen partial pressure and temperature on the grade of ferronickel and iron oxide is evaluated. The NiFe<sub>2</sub>O<sub>4</sub> mineral used in this experiment was synthesized by physical mixing of NiO and Fe<sub>2</sub>O<sub>3</sub> powder, followed by calcining at 1200 [U+2103] for 24 hours in an air atmosphere. The reduction behavior of the synthesized NiFe<sub>2</sub>O<sub>4</sub> is analyzed by TGA and XRD. As a result of the selective reduction of Ni in NiFe<sub>2</sub>O<sub>4</sub>, it is confirmed that the ferronickel and iron oxide (magnetite, wustite) are formed in experimental conditions. Using bromine-methanol leaching method, the composition of ferronickel in leaching solution is quantitatively analyzed by ICP-OES analysis, and the equilibrium phase of coexisting iron oxide was analyzed by XRD.

**Sintering / 119****INFLUENCE OF MAXIMUM TEMPERATURE, HOLDING TIME AND COOLING RATE ON THE STRENGTH OF SINTER ANALOGUES**Mr. HARVEY, Tobin<sup>1</sup><sup>1</sup> *The University of Newcastle Australia***Corresponding Author(s):** tobin.harvey@uon.edu.au

Typically a large proportion of the ferrous burden charged to the ironmaking blast furnace is iron ore sinter. The quality of iron ore sinter has a strong influence on the productivity and fuel efficiency of the furnace, therefore high quality sinter is desirable. Individual pieces of sinter product from industrial sinter strands and sinter pot test are variable in composition and structure. This is caused by heterogeneous distribution of raw materials and spatial differences sintering conditions (temperature profile and pO<sub>2</sub>), and complicates analysis of sintering mechanisms. To reduce the variability in sinter samples an infra-red rapid heating furnace was used to produce laboratory scale analogue sinter tablets under tightly controlled conditions. The tablets were made from nuclear ore particles (1.0-0.71 mm) and fluxed ore ultra-fines (-0.25 mm). The mechanisms driving changes in sinter structure and mineralogy, and the subsequent impact on sinter quality, were investigated using scanning electron microscopy (SEM), optical microscopy, BET and high resolution X-ray CT. The quality of the laboratory scale sinters was measured using an axial compression strength test and a modified reducibility test.

**Sintering / 120****DEM ANALYSIS OF GRANULE SIZE SEGREGATION IN IRON ORE SINTERING****Author(s):** Mr. LI, Chengzhi<sup>1</sup> ; Prof. HONEYANDS, Tom<sup>1</sup>**Co-author(s):** Dr. MORENO-ATANASIO, Roberto <sup>2</sup> ; Dr. O'DEA, Damien <sup>3</sup><sup>1</sup> *CIMR, Chemical Engineering, University of Newcastle, Australia*<sup>2</sup> *CAPPT, Chemical Engineering, University of Newcastle, Australia*<sup>3</sup> *Principal Technical Marketing, Marketing Iron Ore, BHP Billiton, Australia***Corresponding Author(s):** c3201028@uon.edu.au

Size segregation of the iron ore granules packed on a sinter strand has a significant influence on both airflow rate and temperature distribution through the bed. Therefore, it is a key factor that governs the efficiency of mass and heat transfer down the sinter bed. For a defined sinter feed and granule size distribution, it is possible to increase the size segregation through optimising the operating parameters in a sintering process. In this paper, a numerical study was carried out using a 3-D model developed by Discrete Element Method (DEM) to investigate the influence of feed rate and the inclination of rill plate on the level of granule size segregation down the bed. The optimal combination of these two parameters for obtaining a desirable level of size segregation was also studied. These simulation results were validated using a 1/3 scale laboratory sinter strand utilising iron ore granules.

**Sintering / 121****DEVELOPMENT OF GRANULATION AND FIRING TECHNOLOGY IN USING LARGE QUANTITY OF MAGNETITE FINE ORE****Author(s):** Mr. OSUGA, Koji<sup>1</sup>**Co-author(s):** Mr. MATSUMURA, Toshihide <sup>1</sup> ; Dr. NOZAWA, Kentaro <sup>2</sup> ; Mr. MIYAGAWA, Kazuya <sup>1</sup><sup>1</sup> *Kobe Steel, Ltd.*<sup>2</sup> *Kobe Steel, Ltd*

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Kakogawa Works of Kobe Steel, Ltd. has a set of sinter and pellet plants for the production of blast furnace raw materials. Recently, the use of magnetite fine ore has attracted attention while deterioration of iron ore grade. We clarified the problem of granulation and firing in using large quantity of magnetite fine ore, and developed countermeasures.

**Modelling and simulation in coke and ironmaking / 123**

## **THERMAL FLUID ANALYSIS IN DEFORMING PACKED BED**

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The cohesive zone of the blast furnace generates major part of the pressure drop. It is considered that the thickness of the cohesive zone increases with decreasing the reducing agent rate and increasing the usage of the low grade raw materials in future. Thickening the cohesive zone increases the pressure drop and the failure of the blast furnace operation could occur in the extreme condition. Thus the thickness of the cohesive zone should be decreased or permeability of the cohesive zone should be improved. A mathematical simulation technique for the fluid flow and heat transfer in the packed bed of the deforming particles like the cohesive zone was developed. This technique combined the discrete element method for bed deformation and the computational fluid dynamics for the gas flow. Additionally the inter-particle heat exchange in the deforming packed bed was formulated and linked with the discrete element analysis. This mathematical model successfully revealed the variation of the heat transfer mechanism with the deformation of the packed bed. The simulation results could give the useful information for designing the burden distribution under the low carbon operation of the blast furnace.

**Postersession and Coffee Break / 124**

## **ANALYSIS ON THE COMBINED FORM OF IRON SKULL ON THE CARBON BRICK SURFACE USED IN BLAST FURNACE HEARTH**

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The blast furnace (BF) crucible breakout is not uncommon. More and more attentions have been paid on the penetration of molten iron and hearth lining erosion of BF. The iron skull, which is a layer of iron attached on the inner surface of the lining, provides a barrier between carbon brick and molten iron. Formation of a stable iron skull on the inner surface of the hearth lining could largely protect the carbon brick and extend BF campaign life. In this work, the molten iron in condition of high pressure was simulated to figure out the penetration between carbon brick and molten iron in the BF. The influence on combined form between iron skull and carbon brick during the campaign life of blast furnace was also discussed. The experimental samples were analyzed by X-ray diffraction, scanning electron microscopy to explore the distribution of microstructure between carbon and iron inside the carbon-iron composite material. This work is expected to have a guiding significance for prolonging the campaign life of blast furnace.



**Blast furnace ironmaking / 128****INTERACTION BETWEEN LUMP ORE AND SINTER UNDER SIMULATED BLAST FURNACE CONDITIONS****Author(s):** Dr. LIU, Xinliang<sup>1</sup>**Co-author(s):** Prof. HONEYANDS, Tom<sup>1</sup>; Dr. MITRA, Subhasish<sup>1</sup>; Prof. EVANS, Geoffrey<sup>1</sup>; Dr. O'DEA, Damien<sup>2</sup><sup>1</sup> *The University of Newcastle Australia*<sup>2</sup> *BHP Billiton***Corresponding Author(s):** xinliang.liu@newcastle.edu.au

Many efforts have been made to investigate the softening-melting (SM) behaviour of ferrous burden material as it governs the formation of the cohesive zone (CZ) inside the ironmaking blast furnace (BF). Usually, the SM property of individual lump ore is thought to be inferior to iron ore sinter, however, it has been demonstrated that results for a mixed burden of  $\approx 80\%$  sinter and  $\approx 20\%$  lump ore are equivalent to the results obtained using only sinter. In this work, the high temperature interaction between a sinter of high basicity and Newman Blend lump ore from Australian is studied through interrupted SM tests at a number of temperatures. The structural and metallurgical aspects of the interaction are examined, e.g., the variation of ferrous burden voidage is tested using synchrotron X-ray CT scanning, and the metallurgical interaction studied using optical and scanning electron microscopy. Furthermore, the mechanism for the interaction between sinter and lump ore is identified, and factors controlling the reaction are discussed.

Key words: softening-melting, interaction, lump ore, ironmaking

**Automation and digitalization in coke and ironmaking / 130****APPLICATION OF UP-TO-DATE INFORMATION TECHNOLOGIES FOR ASSESSMENT OF CONDITION AND PREDICTION OF BLAST FURNACE MELTING OPERATION****Author(s):** Prof. SPIRIN, Nikolai<sup>1</sup>**Co-author(s):** Dr. PAVLOV, Aleksander<sup>2</sup>; Mr. POLINOV, Andrei<sup>2</sup>; Prof. LAVROV, Vyacheslav<sup>1</sup>; Dr. ONORIN, Oleg<sup>1</sup>; Dr. GORDON, Yakov<sup>3</sup><sup>1</sup> *Ural Federal University*<sup>2</sup> *MMK*<sup>3</sup> *Technical Director, Hatch***Corresponding Author(s):** iakov.gordon@hatch.com

Modern Iron & Steel Works as a rule are equipped with powerful distributed control systems (DCS) and databases. Implementation of DSC system solves the problem of storage, control, protection, entry, editing and retrieving of information, as well as creation of the necessary reporting data. At the same time, Russian domestic and international experience shows that improvement in quality, energy efficiency, resource conservation and competitiveness at the global market require further advance of information systems used for process control and production management. The complex of mathematical models is a foundation of information technologies which support decision making process. The user of these technologies has the possibility to obtain the missing information he needs to make a decision by establishing a dialogue with the mathematical model.

Control of blast furnace operation is often classified as poorly structured problem. Because of this the base mathematical models have to be used at automated workstations of engineering and technological staff of blast furnace. The software for computer decision-making support system is a set of information-connected interactive (dialog) program modules integrated into a common environment. Integration of mathematical models is based on the application of both common initial data and the results of calculations performed by individual modules. Software modules implement mathematical models of heat-exchange, slag, cohesive zone, blast and gas-dynamics

regimes of blast furnace. This forms the basis of functionality of the decision making support system while the modular structure ensures its extensibility.

As an example, for Magnitogorsk I & S Works (MMK) conditions usage of “cohesive zone” model helped to find the necessity of mixing of basic sinter and acid pellets before charging to the furnace to reduce extend of cohesive zone from 3 m to 1.5 m, which improved gas-dynamics , increased productivity and reduce coke rate at blast furnace.

Solution of the problems of analysis and forecast of blast furnace operating parameters using available actual information on furnace performance requires decomposition of the problem into three main interrelated subsystems: the thermal condition of the furnace, blast and gas-dynamics regimes of blast furnace, slag regime. The basic principle, which underlies the choice of specific mathematical equations to describe the individual subsystems, is to resolve the contradiction between the complexity of the modeled process and the need to resolve the technological problems in real time in course of the process and for a specified time interval using the actual available information.

**Keynote / 134**

## **Modeling inner phenomena of self-reducing agglomerates under external inert gas atmosphere**

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The self-reducing phenomena has been explored with the aim of improving the reducing velocity of agglomerates during hot metal production. The inner phenomena taking place in the agglomerates, however, are still controversial and further studies are demanded. In this paper we proposed a detailed mechanism taking place within the agglomerates during the solid-gas self-reducing step. In order to study the inner phenomena, a comprehensive mathematical model is proposed which takes into account the gas inner flow and chemical species transport, with heat supply using inert external atmosphere. The detailed mechanism taking into account gas and solid reactions are discussed and the controlling mechanisms of heat and mass transport are discussed in light of the coupled reactions mechanism. The results are obtained experimentally using isothermal runs and numerically to fit the experimental data and inversely determine the kinetic parameters of the proposed model. It is found that the heat transfer process is the controlling mechanism for the self-reducing step with deficit of carbon at lower temperatures while at high temperatures the mass controlling mechanism plays important role.

**Sintering / 136**

## **CONTROLLING OF FUEL PARTICLE SIZE TO MINIMIZE DUST EMISSION AND IMPROVE PRODUCTIVITY IN IRON ORE SINTERING PROCESS**

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Recently, steel industry confronts a high risk of deterioration of Iron ore property as well as mitigation of green-house gas and particulate in response to the environmental regulation. For particular, iron ore sintering in the integrated steelmaking process generates a high level of particulate due to use of fine ore. It is impossible to recover energy through by-product gas

like BFG and COG in blast furnace and coke oven. In addition, the use of fine coke breeze and anthracite as fuel source for the sintering of iron ore particles is an environmental inferior process. The purpose of this study, therefore, is to figure out the optimal size of the fuel, which is only controllable parameter except that of the iron ore, in order to achieve the mitigation of environmental issue and improve productivity. First of all, the criteria on optimal particle size of the fuel guaranteeing both minimum amount of fine particles in exhaust gas and maximum productivity has been set up through a lab scale pot test. Secondly, optimized operation condition of rod mill was derived based on the criteria. Lastly, result of lab test was compared with that of plant test. As a result, the optimal fuel size is about  $2.4\pm 0.2\text{mm}$  that makes sure to improve the productivity without reducing strength. In order to achieve the purpose of study, it was confirmed that the rod mill must run at charging rate of 45t/h of the fuel with 150 rods. It was shown that the productivity improved by 2% and level of particulate in the exhaust gas reduced by 7% at the operating condition in long term plant test. Consequently, the results of this study might be thought to contribute to partially solving issues on reduction in productivity and increasing fine particulate due to increased fine iron ore.

### Blast furnace ironmaking / 137

## DESIGN AND APPLICATION OF BLAST FURNACE LONGEVOUS COPPER COOLING STAVE

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Since 21 century, the application of copper cooling stave has been an important technical measure to prolong the campaign life of modern blast furnace. Combined with the application of blast furnace copper cooling stave at Shougang Qian'an steel plant, the optimum design of copper cooling stave heat transfer research and structure parameters are discussed. The heat transfer parameters, structure design and installation method of the copper cooling stave are introduced in this paper. The blast furnace engineering design and over 13 years operating practice of the copper cooling stave for No. 1 blast furnace at Shougang Qian'an steel plant are expounded.

### Smelting reduction / 139

## EXPERIMENTAL STUDY ON THE BURDEN DISTRIBUTION IN A COREX-3000 MELTER GASIFIER

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In order to simulate synchronous distribution of coal (coke) and DRI (ore) in the Melter Gasifier of COREX-3000, with down moving of perimeter zone of char bed, we have studied by laboratory experiment effect of charging pattern and kind of material on the stock pile shape, distribution of ore/coal ratio, distribution of porosity and particle size segregation on radius direction. The differences of distribution of ore/coal ratio and porosity on radius direction for two typical burden distribution pattern and distribution model had been analyzed based on discrete element method (DEM). The experimental results under different charging pattern and kind of material show that, the stock pile shape presents a steamed bun shape that is the center of stock was higher but the edge of stock was lower; The charging angle range of ore, coal and the particle size of material have important effect on the distribution of ore (pellet, sinter) / coal (coke) ratio on radius direction; The porosity of burden was higher at center and edge area of the stock but lower at middle area of the stock; For the charging pattern that the angle range of ore is the same of coal (coke), the particle size segregation of materials on radius direction was smaller. The DEM simulations results showed that the pellets distributed more at middle area between two adjacent DRI Flap. In addition, under certain distribution pattern, the stock pile shape, distribution of pellets and distribution of ore/coal ratio on radius direction were big difference, for charging model of "in→out" and "out→in".

## Sintering / 140

**CRYSTAL PHASES IN CaO-FeO-Fe<sub>2</sub>O<sub>3</sub> SYSTEM TRANSFORMED FROM CaO-Fe<sub>2</sub>O<sub>3</sub> SYSTEM UNDER A HIGH COOLING RATE IN AIR**Prof. KASHIWAYA, Yoshiaki<sup>1</sup><sup>1</sup> *Kyoto University, Department of Energy Science and Technology***Corresponding Author(s):** kashiwaya@energy.kyoto-u.ac.jp

A CaO-Fe<sub>2</sub>O<sub>3</sub> system is a fundamental binary system for the iron ore sintering process. Although the basic reactions have been investigated since the 1960s, melting and solidification caused by the combustion of coke results in an unstable state owing to extreme temperature variations. In this study, using a hot thermocouple method, samples of 10% CaO-90%Fe<sub>2</sub>O<sub>3</sub> and 20%CaO-80%Fe<sub>2</sub>O<sub>3</sub> were melted on a thermocouple and quenched with several techniques. The obtained samples were precisely examined by XRD. It was found that the sample containing 10% CaO-90% Fe<sub>2</sub>O<sub>3</sub> changed to 10% CaO-13% FeO-77% Fe<sub>2</sub>O<sub>3</sub> under an oxygen partial pressure (PO<sub>2</sub>) of 0.21 during melting. For the 10% CaO sample, the crystal phases found at a low cooling rate (509 K/s) were WF<sub>ss</sub>, C4WF<sub>8</sub> (C: CaO, W: FeO, F: Fe<sub>2</sub>O<sub>3</sub>), and C2W4F<sub>9</sub>. When the sample composition was 20% CaO, the precipitated crystal phases were C4WF<sub>4</sub>, C4F<sub>7</sub>, and C4WF<sub>8</sub>. On the other hand, the crystal phases for high cooling rates (1590 K/s and 7900 K/s) with 10% CaO were WF<sub>ss</sub> (solid solution of WF and F), F, and C2W4F<sub>9</sub>. The formation of the equilibrium phases WF<sub>ss</sub>, F, C4WF<sub>4</sub>, and C4WF<sub>8</sub> can be understood by examining the isothermal section of the phase diagrams, while the unstable phases C2W4F<sub>9</sub> and C4F<sub>7</sub> are discussed on the basis of the reactions under an equilibrium state.

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**COMPARING THE RESULTS OF ACOUSTO ULTRASONIC-ECHO (AU-E) WITH PHYSICAL MEASUREMENTS FOR SEVERAL BLAST FURNACE HEARTH REFRACTORY LININGS****Author(s):** Dr. SADRI, Afshin<sup>1</sup>**Co-author(s):** Mr. SZYPLINSKI, Peter <sup>2</sup> ; HENSTOCK, Mitchel <sup>2</sup> ; Mr. FILATOV, Sergey <sup>3</sup> ; Mr. SOKOLOV, Alexander <sup>4</sup> ; Dr. GORDON, Yakov <sup>5</sup><sup>1</sup> *Hatch Global Director of Non-Destructive Testing (NDT) Group*<sup>2</sup> *Hatch*<sup>3</sup> *Managing Director, NLMK*<sup>4</sup> *Severstal*<sup>5</sup> *Technical Director, Hatch***Corresponding Author(s):** afshin.sadri@hatch.com

The parameter that has the largest impact on the campaign life of a blast furnace is the health of the hearth refractory lining. When this lining is severely deteriorated, the furnace must be shut down for either a repair or a relining. This means that it is crucial to continuously monitor the health of the hearth refractory lining. However, this has proven to be difficult in the past due to the obscurity and inaccessibility of a blast furnace hearth. To date, the most common method of monitoring the hearth lining has been to measure the temperature of the hearth and corresponding heat fluxes. While this information is useful, it can often be inaccurate and inconclusive when calculating the thickness of the hearth refractory lining. To accurately measure refractory lining thickness, Acousto Ultrasonic-Echo (AU-E), a technology based on the stress wave propagation principals, was developed in late 1990s. AU-E can accurately detect refractory and skull thicknesses, as well as the position of cracks, joints and gaps within the refractory. As advances in technology bring blast furnaces into the modern era of data collection, interpretation and analysis, AU-E will play an important role in making informed decisions, increasing efficiency, and extending campaign life.

In this paper, we present a brief scientific background on the AU-E technique and describe its application for monitoring the hearth refractory lining in blast furnaces. Case studies which have provided lessons learned are also presented to demonstrate comparisons between AU-E and temperature measurements with drilling and physical verifications.

Postersession and Coffee Break / 142

## BEAD - FORMING EXPERIMENT OF BLAST FURNACE SLAG BY GAS SLAG QUENCHING

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Blast furnace slag(BFS) is the most important by-product in iron and steel industry. Due to its high output and high slag temperature, the BFS is a very good heat source. Recovery of sensible heat from BFS is essential for saving energy, reducing emission and improving energy utilization efficiency in iron and steel industry. The process of bead-forming of BFS by gas quenching can effectively recover the waste heat energy of BFS and improve added- value of the BFS product. This paper studies the influence of slag basicity, nozzle and gas quenching pressure on granules' diameter distribution and bead-forming effect by gas quenching. The experimental results show that the slag granule diameter distribution obeys normal distribution and the peak of BFS granule diameter appears at 1mm-2.5mm; the bead-forming effect by gas quenching is the best when the basicity is controlled at 1.2, the mach number of laval nozzle is 1.6, and gas quenching pressure is 0.3MPa.

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## THE CO-LIQUEFACTION OF LOW-RANK COAL/BIOMASS BY N-METHYL-2-PYRROLIDINONE AT HIGH TEMPERATURE

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**Abstract:** In order to effectively use of low rank coal and biomass, the co-liquefied product was extracted from two kinds of low-rank coals and biomass by N-2-methyl-2-purrolidinone(NMP) at high temperature and high pressure. The structures of the co-liquefied product and residues were characterized by element analysis, FT-IR spectra. The effects of temperatures, coal rank, solid-liquid ratio and extraction time on the extraction yields of co-liquefied product were studied, respectively. Moreover, the extraction mechanism of the co-liquefied product at mild conditions is proposed. The results show that the ash contents of the co-liquefied product from two raw coals and biomass are significantly lower than that of raw coals, and the volatile contents and H/C are significantly improved. For GD coal, with the increase of temperature, the extraction yield of GD is improved evidently from 20[U+FF05] to 51.25[U+FF05] and the ash content is decreased from 0.68[U+FF05] to 0.33[U+FF05]at 360 [U+2103].

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## THERMODYNAMIC ASPECTS OF HYDROGEN PLASMA SMELTING REDUCTION OF IRON OXIDES

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Hydrogen plasma smelting reduction (HPSR) is now an established alternative to be considered for upgrading existing ironmaking process and reducing the emission of greenhouse gases. HPSR offers thermodynamics and kinetics advantages over conventional carbo-thermic reduction of iron ores. This process provides improved reducing conditions by the application of hydrogen in the plasma state and high temperature to intensify the reduction processes, henceforth not only enables the feasibility of producing iron in a one-stage process, but also avoids introducing carbon in the product, which in turn makes the metallurgical equipment smaller. In HPSR process, plasma is generated by passing an electric current through a mixture of argon and hydrogen gases which is injected to the plasma arc zone in the reactor via the hollow graphite electrode. Electrons, which are accelerated particles, are responsible to transfer energy in plasma atmosphere. Electron collision with hydrogen molecules leads to create excited species of hydrogen (H, H<sup>+</sup>, H<sub>2</sub><sup>+</sup>, H<sub>3</sub><sup>+</sup>), therefore the number of free electrons in plasma state, degree of ionization and the lifetime of excited particles should be considered due to their influence on reduction reactions. Moreover, the density of the hydrogen-activated species in plasma, which defines the ionization rate of hydrogen, is a function of temperature and the number of injected molecular hydrogen in the arc zone. This study provides an overview of the following items: 1. Atomic collisions 2. Creating plasma by collisional processes in a plasma arc reactor 3. Degree of ionization 4. The thermodynamic principles of iron oxides reduction by hydrogen 5. Comparison of the reduction ability of hydrogen species in plasma state. As a result, the reduction rate with hydrogen is two orders of magnitude faster than those with other reducing agents. In addition, hydrogen plasma smelting not only provides the most environmental friendly steel making, but also produced steel in this way is cheaper than the conventional steel making routes.

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## INFLUENCE OF OPERATION PARAMETERS ON DESULFURIZATION OF HOT METAL IN COREX PROCESS

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COREX process has obvious advantages in environment protection but still has some disadvantages, for example, the content of sulfur in hot metal is high and fluctuant severely. In the present work, the effects of the slag ratio, temperature of hot metal, binary basicity (R<sub>2</sub>) and the ratio of MgO/Al<sub>2</sub>O<sub>3</sub> of the slag on the sulfur content in hot metal are investigated. Correlation analysis and regression analysis are used to analyze the qualitative and quantitative relationships between operation parameters and sulfur content of hot metal based on actual plant data. Experiments are conducted to verify and develop it. Considering interactions between the slag and hot metal, experimental results shows that the operation parameters that have negative relationships with S content in hot metal are temperature of hot metal, R<sub>2</sub>, MgO/Al<sub>2</sub>O<sub>3</sub>. On the contrary, slag ratio is positive correlation parameter.

**Blast furnace ironmaking / 150**

## COKE TEXTURE AS COKE PERFORMANCE PARAMETER FOR THE BLAST FURNACE

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Coke quality plays an important role in the blast furnace process. The current coke quality parameters used in Tata Steel, IJmuiden are the I40, I10 and CSR. With the introduction of more different types of coals there is a need for a more detailed characterisation of the coke. Especially for the behaviour of coke in the lower parts of the blast furnace a parameter is lacking. Previous research indicated coke texture as a promising candidate. A project was setup aimed at identifying the value of coke texture as a coke quality parameter for the blast furnace. For this evaluation a set of coke types based on industrial blends were produced with a variation in coke texture, charge density and grain size of inertinite.

The coke texture measurement was evaluated first. One manual and two automated coke texture measurement techniques were used and compared. After the coke texture was established a range of tests were performed with the different coke types. These included the standard coke parameters like strength, CSR and ash chemistry, but also porosity measurements, reactivity test under blast furnace conditions and dissolution tests. In the dissolution tests heat treated samples of all coke types were included. Of these heat treated samples the degree of graphitisation was measured.

Conclusions on the suitability of coke texture as a coke performance indicator for the blast furnace can be drawn based on the results of the various tests. Some interesting conclusions can be drawn from the coke dissolution experiments with heat treated coke samples. And some interesting relations were found between the sulphur level and the final carbon content of the hot metal in the experiments.

**Cokemaking / 151**

## CHARACTERISING THE INTERFACE BETWEEN IMDC AND RMDC USING MICRO-CT IMAGING

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In recent years we have conducted integrated mechanistic studies to understand the structures controlling coke strength and how these structures form in the plastic layer. These have involved micro CT studies of coke structures and calculation of the response of these structures to stress as well as fractographic studies of fracture surfaces in coke. A number of studies have identified that the boundary between inert maceral derived components (IMDC) and reactive (fusible) derived maceral components (RMDC) in coke can be a source of weakness in the coke. In particular fractographic studies have identified a number of boundary types, depending on how well the IMDC-RMDC are bonded. This study looks at characterising the IMDC-RMDC boundary in 3 dimensions using micro computed tomography (micro-CT). Hand picked coal inerts (1-2mm) were placed in a bed of hand picked vitrinite (<1mm particle size, 5mm diameter bed) in a graphite crucible, sealed and then heated to 1000oC. Micro CT images were collected at the IMBL (imaging and medical beamline) Australian Synchrotron. The non-fused carbon (IMDC) was identified in the image using standard image analysis and an envelope ~200 microns wide drawn around the IMDC. The pore properties of this region were compared with the bulk region of the sample. By sourcing the vitrinite and inertinite from different coals the interactions between macerals of different rank and geological measures could be studied.

**Blast furnace ironmaking / 153**

## DEVELOPMENT AND APPLICATION OF NEW LONG CAMPAIGN TECHNOLOGY OF BLAST FURNACE

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Hearth and high heat load region are key factors affecting the campaign life of blast furnace, mainly for the erosion of carbon bricks lined on furnace bottom and hearth and damaged of cooling equipment of high heat load region. In this paper, the long life of high heat load region was studied. And the new furnace longevity technology in the area was developed, which was combined cooling structure of cast iron cooling stove inlaid with copper cooling strips. It puts forward the design concept of bosh region of thin-wall furnace, and introduces the application of the new technology in two domestic 1080m<sup>3</sup> blast furnaces. The practice showed that the technology had the characteristics of large cooling strength and stability of slag skin benefited from special structural design, which can effectively solve the problem of cooling equipment damage in the area of high heat load of the furnace. In addition, it has low investment and wide adaptability. As a new technology of long campaign life of blast furnace, it can effectively prolong the life of blast furnace, and has broad application prospects.

**Sintering / 156**

## REACTIVE WETTING OF CALCIUM FERRITE ON TiO<sub>2</sub> SUBSTRATE AT 1523K

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The wetting behavior of calcium ferrite (CF) slag on TiO<sub>2</sub> substrate at 1523K was investigated using an improved sessile drop method. The initial apparent contact angle was 30°-50°, and the final apparent contact angle was less than 20°. The CF-TiO<sub>2</sub> system is reactive wetting system, and the wetting process was divided into four stages. Stage I: physical spreading; stage II: reaction at the interface controlled spreading; stage III: reaction at the triple phase line controlled spreading (spreading on CaTiO<sub>3</sub>); stage IV: Equilibrium. The interfacial microstructure of residual slag after wetting was roughly divided into three layers. The top layer of residual slag was composed of CaTiO<sub>3</sub> and Fe<sub>2</sub>O<sub>3</sub>, the middle layer was composed of CaTiO<sub>3</sub> and Fe<sub>2</sub>TiO<sub>5</sub>, and the bottom layer was composed of Fe<sub>2</sub>TiO<sub>5</sub>. The mechanism of interfacial chemical reaction was discussed using the coexistence theory of slag structure, and the results indicating that the formation of CaTiO<sub>3</sub> was mainly in the initial reaction process, then was the formation of Fe<sub>2</sub>TiO<sub>5</sub> in the final reaction process.

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## HEARTH RECOVERY – AN EXPERIENCE WITH USIMINAS BLAST FURNACE#1

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In 2008, after the Blast Furnace#1 shut down, was identified an abnormal phenomenon in its hearth which required great team effort for proper recovery of the refractory and resumption of



operation. At the time, it was aimed to extend the campaign in five years. In this paper, it is described the general aspects of the equipment, the situation in his hearth, actions taken and the current hearth's condition, after further shut down due to the worsening economic crisis in Brazil. As main conclusions: (i) the abnormal condition found in the Blast Furnace#1's hearth was not associated with the refractories' quality, that had preserved their properties; (ii) the repair done, in order to extend the blast furnace campaign in five years, was extremely efficient; and (iii) the Blast Furnace#1's operation between 2010 and 2015 was properly done contributing to the preservation of the hearth, which did not show brick's wear in that period.

#### Modelling and simulation in coke and ironmaking / 159

### DEM-CFD MODELLING OF THE TRANSIENT, MULTIPHASE FLOW IN THE HEARTH OF A BLAST FURNACE

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Steelmaking following the blast furnace process route has a share of approximately 75 % of the worldwide steel production and thus is the primary source of steel. Due to the large size of blast furnaces and the extreme process conditions therein, the accessibility for measurements inside the furnace is very limited. Nevertheless, since the campaign life is closely related to the multiphase processes in the lower part of the blast furnace, the hearth, it is important to understand the observed phenomena. Mainly the transient movement of the packed coke bed ("floating" or "sitting" dead man), the shape of the resulting coke free region and their dependence on different operating conditions are of particular interest.

In the past, various (experimental, analytical and numerical) models have been developed to understand and describe the interacting multiphase flow and the thermo-chemical processes inside the blast furnace. These models can be generally subdivided in continuum approaches at the macroscopic and discrete models at the microscopic scale. With increasing computational capabilities the discrete approaches, especially the Discrete Element Method (DEM), have been applied in many fields of research; for instance in geomechanics, physics, pharmacy and (chemical-)engineering. The great advantage of these approaches is the temporal and spatial resolution of the mechanical interaction among individual particles of different size and shape and with their surrounding in granular systems. Furthermore, it is possible to extend these approaches with CFD models to describe the interaction between solid, gaseous and liquid phases in technical, multi-phase systems.

The publication presents a numerical DEM-CFD study of an isothermal blast furnace model of a plant located at the "AG der Dillinger Hüttenwerke" in Dillingen, Germany. The model is calibrated with specifically chosen boundary conditions derived from online measurements and process model calculations. With this calibrated model the impact of different liquid levels on the processes in the hearth is investigated. The results presented focus on particle movement, porosity distribution and the formation of coke free zones in the lower part of the furnace.

#### Sintering / 160

### EFFECT OF CONDUCTIVITY AND MAGNETIZATION OF WATER ON GREEN MIX GRANULATION PROCESS

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Acute crisis of water in the region compelled the usage of recycled water with high conductivity that helped in increasing granulation. However, usage of recycled water beyond 50% has resulted in undesired accretion in the Mixing and Nodulizing Drum. Magnetized water reduced contact angle and improved the granulation of green mix. The effect of magnetization of water was studied by varying magnetic intensity. Contact angle up to 32o was observed against a desired angle of 40-55o for optimum nodulization of the green mix. Conductivity up to 2650 Micro Siemens/sec was found against the normal value of 400. The optimization of contact angle and conductivity of recycled water to control coagulation was mentioned. Anti-coagulant was found to ease the problem, with which the contact angle could be increased to the desired level. The growth of the granules increased with the use of anti-coagulant. Granulation Index in the range of 1.7 could be sustained.

Data of various combinations namely with recycled, without recycled water; with magnetization, without magnetization and with anti-coagulant and without anti-coagulant are presented in this paper. SEM images revealed strengthening of water bond with increasing conductivity. Ultra fines coagulated better with increasing magnetization. Growth was predominantly high with use of anti-coagulant.

**Keynote / 161**

## COMPARISON OF BLAST FURNACE OPERATION MODES IN THE WORLD

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The blast furnace is worldwide the dominant metallic product supplier for crude steel production. It has reached an extreme high technological standard with large efficiency and low reductant rates. Independently from the fact that the blast furnace has nearly reached its theoretical minimum in energy consumption it enables the operators a wide range of operation modes with a high flexibility.

This varies depending on regional and other circumstances in manifold possibilities regarding ferrous burden structure, reductant rates like use and amount of auxiliary reductants and coke rates, productivity levels and oxygen injection rates and the durability in blast furnace campaigns. One aspect are the requirements on the quality of ferrous burden materials and blast furnace coke.

Amongst these items the report also discusses single blast furnace highlights and points out the possible future survival of this process under the given political discussions on CO2 mitigation.

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## SIMULATION OF BURDEN CHARGING IN A BLAST-FURNACE EQUIPPED WITH A BELL-LESS TOP SYSTEM USING DISCRETE ELEMENT METHOD

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To achieve a stable and efficient blast furnace operation it is important to have a controlled gas flow inside the furnace with a proper burden distribution, thus a strict control of the particulate material size distribution inside the charge is required to avoid generation of preferential paths of the gas molecules through the burden. This work uses Discrete Element Method (DEM) to simulate raw material loading into a blast furnace equipped with a Bell Less Top (BLT) system. The simulations were based on a real operation of a steelmaking plant in Rio de Janeiro. The simulations allowed the evaluation of the contribution of the physical properties of the raw materials fed into the furnace such as size distribution, shape, density and mechanical resistance, as well as the effect of the rotating chute of the BLT system on the loading of coke and the metallic burden constituted of sinter, iron ore and pellet particles. The effect of wear on the rotating chute were also investigated. Also, a post-processing tool was developed that allowed a qualitative and quantitative analysis of the DEM simulation results in terms of particle size and component segregation at the top of the blast furnace. Thus, this work establishes the foundations of a methodology that allows search for an optimum rotating chute algorithm as function the burden properties.

**Smelting reduction / 165**

## TECHNICAL IMPROVEMENT AND PRODUCTION OVERVIEW OF SHANDONG MOLONG HISMELT PROCESS

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The only HIs melt process in the world was moved from Kwinana, Australia to Shandong, China in 2013 and all the related copyright has also been transferred from Rio Tinto to a Chinese company in 2017. The Shandong HIs melt plant was put into operation in June, 2016 and it has achieved 70-day continuous operation with the highest daily production being 1876 t/d. This is the first time to achieve continuous industrial and commercial operation of HIs melt process without the utilization of coke and iron ore aggregates. During the construction and operation process in the past 5 years, a lot of technical improvements such as process innovation with rotary kiln furnace, optimization of smelting reduction vessel (SRV) system, adoption of new refractory materials, operation improvement with intermittent tapping, etc., have been made. Meanwhile, the operation indexes were improved compressively compared with the indexes of Kwinana HIs melt plant. An overview of those operation indexes were also introduced in this paper. The successful operation of Chinese HIs melt plant with low cost will promote the advancement of the ironmaking by replace part of blast furnace iron production capacity with sustainable and green HIs melt process.

**CO2 reduction and energy saving / 167**

## RESEARCH DEVELOPMENT ON UTILIZING BIOMASS IN THE BLAST FURNACE FOR CO2 EMISSION REDUCTION: EXPERIENCES FROM NORDIC COUNTRIES AND CANADA

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Within the integrated steel plant, the blast furnace BF is the most energy intensive process with significant amount of CO<sub>2</sub> emission. Switching of fossil fuels to biomass offers an alternative for the natural resources reservation and climate change mitigation. In recent years, lots of efforts have been putting on developing biomass for BF's utilization, especially in regions with abundant forest resources. This paper aims to give a review of research development in Sweden and Finland from North Europe and Canada from North America. Biomass availability, market competition, economic feasibility, and barriers and challenges for the industrial applications are addressed.

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## **SIMULATION AND DEVELOPMENT OF MATHEMATICAL MODEL FOR THE BELL-LESS TOP BURDEN DISTRIBUTION ON ANSTEEL**

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**Abstract:** The paper presents a brief introduction about the significant work conducted with a scale of physical bell-less burden model for falling curves and burden distribution at any given chute angles. An incidence formula between flow control gate (FCG) and burden flow was established by the actual measurement of charging. The measurement of falling curves using laser trajectory probe at given stockline and any given chute angles was calibrated with the actual measurement data. Based on the above, a burden distribution mathematical model was created in AnSteel. This mathematical model could calculate burden distribution profile and help BF improve operation on thickness of layers, profile and ore/coke distribution on diameter direction. **Key words:** Bell-less top, Mathematical model, Burden distribution profile

**Recycling of in-plant residues / 176**

## **THE EXPERIMENTAL STUDY ON THERMAL INSULATION AGENT MADE FROM CDQ DUST ON MOLTEN STEEL**

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**Abstract:** In this paper, on the basis of system of CDQ dust block test, thermal insulation performance test of CDQ dust in laboratory and industrial application is studied, the performance of CDQ dust as thermal insulation agent of molten iron and impact of [S] in iron is comprehensive analyzed, and on the performance of CDQ dust, carbonized rice husk and composite preservation agent etc is comparative tested. The results show that the thermal insulation performance of the CDQ dust as molten iron thermal insulation agent is equivalent to carbonized rice husk, and which is higher than the composite insulation agent, and has no obvious effect on the [S] of molten steel. Compared to carbonized rice husk and composite insulation agent, CDQ dust is directly from the metallurgical enterprises, has stable composition and stable quality, and the quality won't decline by the reason of interference on such as the product cost, raw material source, and other factors. So the CDQ dust has obvious advantages on stable product quality, and have broad application prospect.

**Blast furnace ironmaking / 180**

## **PULVERIZED COAL INJECTION SIMULATION**

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Pulverized coal injection is a commonly used practice in modern blast furnace operation. To further increase the PCI rate, a detailed understanding of gasification kinetics behavior of injected coal in tuyere and characteristics of combustion residues is critical. Using the PCI injection simulation rig at CanmetENERGY, the combustion behavior of selected typical PCI coals was examined. The combustion residues collected were analyzed to quantify the contribution of different types of carbon, namely char, coke and soot, using a TGA technique developed recently at CanmetENERGY. Using the information collected, the transformation of coal into different type of carbon materials during heating and combustion is determined. The collected information enables a direct comparison between coals and allows to optimize combustion conditions to further increase PCI rate.

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## TECHNO-ECONOMIC ANALYSIS OF BIOCARBON DIRECT INJECTION IN BLAST FURNACE IRONMAKING

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Substitution of pulverized coal injection by solid biocarbon fuel has the potential to achieve substantial reduction in GHG emissions from blast furnace ironmaking. A techno-economic model was developed to evaluate the value-in-use of solid biocarbon to facilitate the selection of solid biocarbon for replacement of pulverized coal injection. The value-in-use of solid biocarbon is strongly influenced by its O/C mass ratio as it dictates the cost of raw materials required to support the blast furnace ironmaking process and potential GHG emissions achievable. The major barrier to industrial-scale implementation is the insufficient solid biocarbon production capacity needed to meet the high demand of the industrial steel sector. In order to overcome this challenge, the entire supply chain of suitable biocarbon needs to be developed and expanded.

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## Experimental Blast Furnace Operation [U+FF0D] Outline of Experimental Blast Furnace [U+FF0D]

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In COURSE50 STEP2, integrated verification tests of the mitigation of CO2 emissions and CO2 separation from blast furnaces are being conducted using a newly built 12m3 experimental blast furnace and a 30-t-CO2/day chemical absorption process evaluation plant simultaneously. The experimental blast furnace was constructed in Kimitsu Works and the construction was completed in September 2015. The experimental blast furnace is equipped with 3 tuyeres and 1 taphole. An

injection lance is equipped on each tuyere with the ability to inject pulverized coal, oxygen and reducing gases (COG or other gases). For the hot blast production, 2 top combustion hot furnaces were installed. The maximum blast temperature is 1,100 degrees C. The material handling facility has the capacity to charge 1 kind of coke, 2 kinds of ores and 2 kinds of flux. A distributing chute is used to distribute the material into the blast furnace. A hydraulic taphole opener, mud gun and cover traverser are installed in the cast house. The hot metal and slag, produced in the operation, are received in a pot and cooled into solids before removing the metal and slag from the pot. We have performed 4 experimental campaigns with this experimental blast furnace and have had excellent results.

**Sintering / 185**

## **KEY TECHNICAL CHALLENGES IN SINTER MAKING AT TATA STEEL KALINGANAGAR – USE OF HIGH ALKALI ORES & CONTROL OF HIGH TEMPERATURE PROPERTIES.**

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Tata Steel Kalinganagar is a green field 3MTPA integrated steel plant operating via the BF-BOF route. The sinter plant at Tata Steel Kalinganagar was commissioned in January 2016. The sintering machine area is 496m<sup>2</sup> with state-of-the-art cooler design and advanced high intensity mixing-granulation systems. Among the challenges faced in the ramp up, two key issues that were of major concern in the sinter making process was alkali management due to use of unbeneficiated high alkali ores in pile making and the control of high temperature property of sinter (Reduction Degradation Index, RDI). Due to limited availability and logistic issues of supply to Kalinganagar from Tata Steel's captive iron ore mines at Joda and Noamundi, it was decided to use unbeneficiated iron ore from Khondbond, Odisha. In terms of ore chemistry, Khonbond ore had high alumina and alkali content (0.3% K<sub>2</sub>O as compared to 0.05% for beneficiated ores from Joda and Noamundi). High alkali content leads to higher coke rate, low productivity and affects the furnace lining in the blast furnace. Studies on alkali flushing capabilities of the blast furnace were carried out and based on this, the permissible limit of sinter alkali was determined and threshold for usage of Khonbond ores in base mix pile was fixed.

Permissible limit of sinter RDI is 30, as desired by blast furnace operators at Tata Steel India. Though commissioning of sinter plant at Kalinganagar was carried out in Jan'16, measurement of sinter RDI began in the month of May'16, and was found to be higher than the specified limit of 30%. Sinter RDI varied between 24 and 46 at different regimes of operating parameters and iron ore fines. Based on data analysis, trials were carried out to control the sintering process – in terms of heat input and burn through temperatures. FeO content of sinter at high alumina input conditions was fixed at 9% minimum to maintain sinter RDI below 30 by considering sinter alumina 2.8% max, with reference to past data at TSK. FeO below 9% needs an action on fuel rate to increase in steps after considering the burn through point and sinter RDI. It was also critical to control the burn through point so as to minimize on strand cooling which is detrimental due to the formation of secondary hematite, known to reduce sinter strength. Crushing fineness of solid fuel and flux also needed improvement for efficiency of solid fuel consumption and consistency in sinter quality.

**Recycling of in-plant residues / 186**

## **RECYCLING OF THE HIGH-ZINC FRACTION OF UP-GRADED BF SLUDGE WITHIN THE INTEGRATED STEEL PLANT**

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Ore-based steelmaking generates a variety of residues including dusts, sludges, scales and slags. Recycling of these residues within the process or via other applications is essential for sustainable production from both environmental and economic aspects. In blast furnace (BF) ironmaking, the gas-cleaning equipment recovers the particles in the off-gas as BF dust and sludge. Traditionally, the dry dust is recycled via the sinter, but in the case of pellet based BF, recycling methods utilizing cold bonded briquettes and injection have been developed. Depending on the BF operation, the main output of zinc from the BF is more or less via the top gas. Therefore, as the dust is recycled, the sludge has to be dezincing prior to recycling to prevent accumulation of zinc in the BF. Although dezincing and recycling of the low-zinc fraction via sinter have been reported, research towards recycling of the high-zinc fraction of BF sludge within the integrated steelplant is lacking. In the present paper, the high-zinc fraction of tornado-treated BF sludge was incorporated in self-reducing cold-bonded agglomerates. The agglomerates were subjected to smelting reduction experiments aiming to study the feasibility of recycling the in-plant residues to the desulfurization plant. Difficulties in the melt-in of the agglomerates suggested that cold-bonded pellets were more suitable for recycling than cold-bonded briquettes. However, full-scale trials suggested that cold-bonded briquettes can be used to recycle in-plant residues to the desulfurization plant without affecting the desulfurization process and final steel quality.

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## THE EFFECT OF UNBURNED PULVERIZED COAL ON THE SLAG VISCOSITY

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**Abstract:** The unburned pulverized coal in the blast furnace has an effect on the slag properties, which affects the quality of the hot metal. The effect of unburned pulverized coal made from Yongcheng anthracite on slag viscosity is studied by means of high temperature melt physical characteristics synthetic test instrument, and the reason of slag viscosity change was illuminated by observing slag surface topography using scanning electron microscope (SEM). The results show that The change of the concentration of complex anions and suspended solids in molten slag is the main reason for the change of slag viscosity. It has a certain dilution effect on the molten slag when the content of unburned coal powder in the slag is 0.2~0.8%, and the slag viscosity increases remarkably when the content of unburned coal powder above 1%.

**Key words:** unburned pulverized coal; slag viscosity; complex anions; surface topography

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## MEASUREMENT OF ACTIVITY OF AL<sub>2</sub>O<sub>3</sub> IN METALLURGICAL SLAG

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**Abstract:** The content of Al<sub>2</sub>O<sub>3</sub> in iron ore is of negative effects on sintering process, metallurgical properties of sinter and smelting of BF, which has a serious influence on the quality of molten iron. So it is very important to study the activity of Al<sub>2</sub>O<sub>3</sub> in metallurgical slag to grasp and control the influence of content of Al<sub>2</sub>O<sub>3</sub> on the quality of molten iron. In this paper, several measurement methods and its present status of Al<sub>2</sub>O<sub>3</sub> activity in different slag systems are reviewed systematically. The achievements of representative studies are introduced and analyzed, both advantage and disadvantage of different methods are explained, and the rationality and accuracy of measurement methods are discussed emphatically. The theoretical analysis shows that the reference slag method can avoid the error caused by thermodynamic data, and has better scientificity and higher precision than other methods. Therefore, the determination of activity of Al<sub>2</sub>O<sub>3</sub> by the reference slag method has important academic value and good application prospect.

**Key words:** activity of Al<sub>2</sub>O<sub>3</sub>; metallurgical slag; measurement method; reference slag method; chemical equilibrium method; e.m.f method

**Blast furnace ironmaking / 189**

## ALKALI IN THE BLAST FURNACE – INFLUENCE OF MODIFIED ASH COMPOSITION IN COKE AND CHARGING PRACTICE

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In the blast furnace (BF) process, the presence of alkalis (Na, K) is known to have negative influences on the process due to the catalytic effect on coke gasification, destruction of carbon structure by intercalation of alkali, scaffold formation and refractory attack. Alkalis are introduced with the raw materials and due to alkali circulation; alkalis are picked-up on the way to the higher temperature zone in the BF. In the combustion zone, a significant part of alkalis are reduced and vaporized. The formed alkali gas follows the furnace gas to the colder regions in the shaft. Here alkali is condensed on the burden or furnace walls and oxidized to more stable compounds. The rather low temperature and less reducing gas in upper part of the shaft are not favorable for alkali gas output via the top gas. Moreover, the solubility of alkalis in slag is dependent on the slag chemistry and amount while higher temperatures in the raceway region enhance the reduction and vaporization of alkalis which will prevent alkali dissolution in slag. The nature of alkali compounds in the BF combined with the character of the process causes alkalis to recirculate and accumulate in the BF. Within this study, the distribution of alkali at different depths in the shaft and for different charging practices has been studied by examination of excavated coke samples from LKABs Experimental Blast Furnace. A possible way of controlling the alkali load in blast furnace have been investigated by studying if alkali can be bound in stable phases in a modified coke ash and coke coating and thereafter drained out from the BF via the slag.

**CO<sub>2</sub> reduction and energy saving / 190**

## CO<sub>2</sub> ULTIMATE REDUCTION IN STEELMAKING PROCESS (COURSE50 PROJECT)

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Japanese steelmakers have executed “development of technologies for environmentally harmonized steelmaking process, ‘CO2 ultimate reduction in steelmaking process by innovative technology for Cool Earth 50’ (COURSE50)” since FY 2008. This is a national project commissioned by the New Energy and Industrial Technology Development Organization (NEDO). The target of COURSE50 is the mitigation of approximately 30% of CO2 emissions in integrated steel plants. For this purpose, two technologies are investigated, which include a) Intensified hydrogen reduction in blast furnace and b) Separation and recovery of CO2 from the blast furnace gas via chemical absorption and physical adsorption methods by the effective utilization of unused waste heat in steel works. The concept of the intensified hydrogen reduction of iron ore is as follows. Intensified hydrogen reduction must ensure the heat balance by decreasing the carbon direct reduction ratio, which is an endothermic reaction. To verify this concept, the experimental blast furnace is constructed in Kimitsu works, Nippon Steel & Sumitomo Metal Corporation. Main methods of decreasing the carbon direct reduction ratio are blast and raw material control. And reasonability of the results is affirmed by comparison between results of three dimensional mathematical calculation model and actual results of experimental blast furnace. The outline of results of the experimental blast furnace are reported and the basic concept is recognized through the experiment.

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## **ANALYSIS OF DAMAGE MECHANISM OF COOLING STAVE OF LAIWU STEEL’S 3200 m3 BLAST FURNACE**

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Copper stave has been widely applied in large blast furnaces especially whose inner volume exceed 2000m3 due to high cooling capacity. In the past years, cooper staves suffered damages in some blast furnace, dwindling the campaign life of blast furnace. For this problem, the damage mechanism of the cooling stave was studied by analyzing the chemical composition, thermal conductivity, metallographic tissue and microstructure in this paper. It was found that the main reason for the damage of the cooling stave was not the cooling stave itself but its working condition. Firstly, the poor quality of the coke and the large furnace angle promoted the development of the marginal airflow, which intensified the erosion of refractory materials, resulting in a large area of slag crust fall-off and the damage of the cooling water pipe. After the remedy, the cooling capacity of the cooling stave was still reduced. And the temperature was easy to rise, especially when the temperature reached 370 [U+2103], the hydrogen embrittlement happened. Those two reasons led to the rapid decrease of the ability of adhering slag. Finally, the erosion of marginal airflow caused the damage of cooling stave.

**Sintering / 193**

## **EFFECT OF ULTRA-FINE IRON ORES ON SINTER PROCESS AND QUALITY**

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The iron ore sintering process is essentially influenced by the permeability of the sinter bed. Higher amounts of ultra-fine iron ores lead to a weak granulation behaviour, which causes lower voidage in the sinter bed and therefore a decreasing bed permeability. Due to this, the application of ores with a size lower than 0.2 mm is limited. In this investigation the amount of ultra-fine ores (-0.1 mm) in the sinter mixture is increased stepwise up to 500 kg/t sinter mixture by using an intensive mixer for mixing and granulating and hydrated lime as binder. Trials in a laboratory sinter pot could show that with this method it is possible handle such high amounts of ultra-fines with only a minor loss in productivity and increase of solid fuel. By using about 300 kg ultra-fines per tonne of sinter mixture no negative changes neither in sintering process nor in product yield was observed. The sinter product was investigated regarding its quality. The sinter strength was measured with the shatter test and showed virtually no decrease with increasing amount of ultra-fines in the sinter mixture. The reduction behaviour of sinter produced from the mixture with 500 kg/t ultra-fines was investigated using a Tammann furnace experimental set and thermo-balance facilities. Isothermal tests were conducted to determine the activation energy; non-isothermal tests were performed under conditions simulating the area of the cohesive zone in the blast furnace; results were compared with those for a reference sinter.

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## THE ROLE OF MINERAL PHASES BY SINTERING OF IRON ORES WITH BIOFUEL

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In recent years, substituting a part of coke breeze with a biomass fuel in the sintering of iron ores has become an attractive research topic, which should help with the minimization of CO<sub>2</sub> released from fossil fuels as well as searching for an alternative for coke in ironmaking. Besides the common process analyses, characterization of sinter properties through the mineralogical composition represents a new challenge. In this study, the mineralogy of iron ore sinters produced with partial fuel substitution with charcoal, milled walnut shells and oak sawdust are described and the basic technical parameters such as the tumble index and temperature are compared. When the fuel substitution is based on the equivalent fixed carbon content, the overall fuel amount in the sintering mixture by using non-pyrolised biomass increases. Because this is caused by the volatile matter, which cannot be fully utilised, no dramatic increase of the temperature of FeO/magnetite content was observed. On the other hand, energy brought due the non-pyrolised biomass is distributed much more uniformly and the ore particle assimilation is then more advanced. Also, higher porosity during the cooling of the hot sinter mass supported the formation of the calcium ferrites. Finally, the tumble index shows that the substitution of the coke breeze in the sintering process generates quality sinters but is limited by pyrolised or non-pyrolised biomass.

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## IRON ORE SINTERING RESEARCH AT DIFFERENT SCALES

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With the rapid change in iron ore supplies and composition, steel mills now have to adjust the composition of the ore mixture to the sinter plant more frequently than ever before. Hence, different scales of test methods have been developed to help sinter plants evaluate new ore types and ore blends in order to optimise their ore mixtures and reduce raw material costs. However,

iron ore sintering is very complex with many interdependent variables. For the same ores, the sinter quality and sintering performance may vary significantly with the scale at which the sintering tests are conducted. Therefore it is important to understand the effect of test scale on sintering performance and sinter quality while interpreting the test results. This paper provides an overview of various techniques which have been developed at different scales in order to evaluate iron ore and improve the understanding of the iron ore sintering process. This is followed by the results of two sinter blends tested at different scales.

**Direct reduction / 198**

## **EXPERIMENTAL STUDY AND FEASIBILITY ANALYSIS ON FLASH REDUCTION IRON MAKING PROCESS**

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Due to the very fast reduction rate and its possibility to get rid of coke and other technical advantages the flash reduction iron making process has drawn a lot of concern by many experts and scholars in recent years. According to relative literatures, the derivative process of flash reduction of iron ore is analyzed. The development of the flash reduction iron making process at home and abroad is introduced. The laboratory research work carried out by the author in terms of flash reduction iron making is mainly introduced in this paper, and the main problems that may be faced in the industrialization of flash reduction iron making process are also discussed.

**Blast furnace ironmaking / 202**

## **BELL LESS TOP® COUPLED WITH ADVANCED MATERIAL SAMPLING: THE ONLY SYSTEM ALLOWING TO KNOW HOW THE BF IS REALLY CHARGED**

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The Bell Less Top Charging System invented and developed by Paul Wurth, is commonly recognized as Best Available Technology in the domain of blast furnace charging. This paper describes how the 2nd gen Bell Less Top, combined with stockhouse improvements and intelligent sampling devices can be used in order to expand blast furnace charging process know-how and to further optimize Blast Furnace charging, allowing in particular better monitoring and control of material segregation. In a first part, different design characteristics of the Bell Less Top and blast furnace charging will be described, including Discrete Element Method models. The second part will discuss stockhouse improvements. Finally, the summary will show how these improvements can be combined in order to control the charging process in a way suitable for every segregation requirements.

**Smelting reduction / 203**

## **CONTROL OF DIRECT REDUCTION IN SMELTING REDUCTION IRONMAKING**

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In two stage-smelting reduction process, it is desirable to decrease the reduction degree of iron ore in a pre-reducing unit by reducing its temperature to avoid any troubles due to stickiness of high reduced iron ore. However, less pre-reduced iron ore can induce direct reduction in a melter-gasifier, which can increase the consumption of coal. In this case, the portion of direct reduction can be determined by the reducibility of Pre-Reduced Iron ore (PRI) and the reactivity of coal with CO<sub>2</sub>. PRI was prepared in the form of pellets, and its reducibility was evaluated at various temperatures in an atmosphere containing H<sub>2</sub>. Coal was carbonized in melter-gasifier condition, and then its reactivity with CO<sub>2</sub> was measured at several temperatures and CO<sub>2</sub>-containing gas mixture. The possibility that direct reduction takes place in a melter-gasifier was high because the PRI pellet was reduced more slowly than unreduced iron ore, and the char reacted more actively than coke. The direct reduction rate in a melter-gasifier was roughly estimated as the product of the CO<sub>2</sub> content in the ascending gas and the reaction rate constant of coal with CO<sub>2</sub>. Based on the diagram, the way of minimizing the portion of direct reduction was discussed.

**Automation and digitalization in coke and ironmaking / 205****REAL TIME ELEMENTAL ANALYSIS FOR PROMPT PROCESS CONTROL IN METALLURGY****Author(s):** Mr. BARYSHNIKOV, Alexander<sup>1</sup>**Co-author(s):** Mr. TIKHONOV, Dmitrii <sup>2</sup><sup>1</sup> LDS<sup>2</sup> DDG cooperation technologies**Corresponding Author(s):** dmitri\_tikhonov@mail.ru

During mining, beneficiation and processing stages in production it's necessary to know chemistry of materials in real-time for optimal process control and improve final product quality. Using online information about chemistry it's possible correct distribute iron ore and concentrate between stockpiles, optimal dosage fluxes and coke for stabilize sinter basicity before it is too late for a process, provide quality control of iron and steel. In report we will talk about laser elemental analyzers for detection in real-time of all necessary elements, including Fe, Si, Ca, Al, Mg, C without sampling directly in site - on a conveyor belt and in a slurry pipeline. This analyzer eliminates expensive laboratory analysis and some hours delay with potential human errors. This analyzer do not produce any ionized radiation and, thus, are fully safe; operate 24/7/365 in the automatic mode under heavy industrial environment many years in metals and fertilizers industries.

**Keynote / 206****UNDERSTANDING COKE FORMATION AND QUALITY BY ANALYSIS OF PHYSICO-CHEMICAL PROCESSES****Author(s):** Dr. MAHONEY, Merrick<sup>1</sup>**Co-author(s):** Dr. JENKINS, David <sup>1</sup><sup>1</sup> University of Newcastle**Corresponding Author(s):** merrick.mahoney@newcastle.edu.au

The conversion of coal into coke is a complex process, involving interrelated phenomena occurring simultaneously. These include heat transfer, gas evolution, softening and resolidification, evaporation and condensation, bubble growth and coalescence, gas transport, shrinkage and fissuring. Moreover, a key aspect of coke quality is its (cold and hot) strength as well as its reactivity. Knowledge of how these competing processes affect the formation and quality of coke is important for optimal outcomes. This work describes a series of research activities based on models, informed by laboratory and pilot scale experiments, of all the above phenomena. Outcomes of the

studies have provided novel mechanistic explanations for internal gas pressure, fissure patterns and spacing, dilatometer measurements, sole heated oven tests, coke microstructure formation and aspects of coke quality. The aim here is to emphasise the value of appropriate models for interpretation and analysis of test results, as well as predicting aspects of coke quality from coal properties and coking parameters.

#### Blast furnace ironmaking / 207

### HIGH TEMPERATURE CHARACTERISTICS OF BLAST FURNACE FERROUS BURDENS

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Blast furnace cohesive zone has a profound impact on the hot metal productivity and quality, fuel consumption, operation stability and lining life of the blast furnace. The high temperature properties of ferrous burden materials determine the configuration and location of the cohesive zone, and have therefore attracted increased attention. While numerous standard testing methods are in use to assess the quality of ferrous burden materials for the blast furnace use, these simple tests are generally conducted at fixed conditions, which often represent the extreme situations encountered by the burden materials in the blast furnace. Furthermore none of these simple tests provides information on the high temperature properties of the burden materials, such as the softening and melting properties. CSIRO is equipped with a fully computerised testing facility to characterise the high temperature properties of the ferrous burden materials under the realistic conditions similar to those encountered in the blast furnace. This paper will first review the test methods developed worldwide for evaluating the high temperature characteristics of blast furnace ferrous burdens and then discuss the softening and melting properties of a variety of blast furnace burden materials including sinter, pellets and lumps, and their implications for blast furnace operation.

#### Blast furnace ironmaking / 208

### PLASMA BLAST HEATING – CONCEPT FOR AN INDUSTRIAL TRIAL

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Hot blast superheating using a hot mixer equipped with plasma torches promises to reduce the blast furnace coke consumption and carbon footprint while increasing blast furnace productivity. Countermeasures to keep the hot blast refractory below its service temperature limit were developed using computational fluid dynamic (CFD) modeling and evaluated at the pilot plant scale. The operation of the hot blast stoves with a plasma torch equipped hot mixer will be explained. The payback period for hot blast superheating ranges from satisfactory to good based on blast furnace cost savings and the value of the additional steel production.

#### Postersession and Coffee Break / 211

### TECHNOLOGY PROGRESS FOR BLAST FURNACE SLAG GRANULATION PROCESS

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According to the comparative analysis of different blast furnace slag granulation methods and water-slag separation processes, we have combined the granulation tank, the innovative filtration process and the heat recovery together to ensure the slag granulation production reliable, energy-saving, environmental friendly, practical, economic and efficient. By the analysis of using grab crane to take out granulated blast furnace slag from the filter tank, we have developed automatic reclaimers for taking out granulated slag. The innovative filtration process has technological advances in technology, equipment research & development, environment technical. The application of the innovative filtration process will provide an innovative technical support, lower running cost & automatic production for iron & steel enterprise.

**Blast furnace ironmaking / 213**

## THE APPLICATION OF THERMALCAMERA IN THE 5800m<sup>3</sup> BLAST FURNACE AT SHAGANG GROUP

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**Abstract:** After the 5800m<sup>3</sup> blast furnace was put into operation in 2009, The Thermal Camera started observing the burden surface and gasflow conditions in the furnace. BF Thermal Camera with high resolution chip was upgraded in 2017. Much clear image of the burden surface and gasflow conditions were obtained. Operators can understand very well the situation inside the vessel all the time. Another dedicated Thermal Camera installed to observe chute movement is used also to watch the condition of around lining board. Thermal Camera is beneficial to assist BF operation and equipment maintenance.

**Keywords:** BF, Thermal Camera, burden surface, gasflow, chute

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## THE APPLICATION OF ONLINE LASER DETECTOR OF BURDEN SURFACE PROFILE IN THE 3200m<sup>3</sup> BF HANSTEEL

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**Abstract:** No.8 blast furnace (3200m<sup>3</sup>) of HanSteel is equipped with an online laser detector of burden surface profile. During the furnace running, images of burden surface can be obtained with laser scanning. All data and curves of the burden profile are processed by computer to provide real-time BF information for operators. This system can be used to detect burden surface profile and help improving BF charging operation. Some irregular furnace circumstances such

asburdendeflection or collapse can be corrected in time to keep the BF running stably and smoothly.

Keywords:blast furnace, onlinelaser detector, burden surfaceprofile

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## **WETTING BEHAVIOR OF GRAPHITE- $Al_2O_3$ SUBSTRATES AGAINST MOLETEN $CaO-SiO_2-Al_2O_3-MgO$ SLAGS**

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Permeability at the cohesive and dripping zones in blast furnace is mainly controlled by the dripping behavior of molten slags in the cokes aggregates layer. Thus, wettability of cokes (graphite) which contains ash minerals should be one of the most important controlling factors on the dripping behavior. In the present study, the wettability of graphite-alumina composites with different alumina contents against molten  $CaO-SiO_2-Al_2O_3-MgO$  slags was investigated at 1873K by sessile drop method. It was found that the composite with the larger alumina content had the better wettability, which is attributed to the intensive interfacial reaction against the molten slags. Moreover, the molten slags with the higher basicity revealed the smaller contact angles on the composite substrate, which is simply due to the higher surface tension of slag. Additionally, with increasing the alumina content in the composite, the longer holding time was required for the equilibrium in interfacial reactions.

**CO2 reduction and energy saving / 217**

## **EXPERIMENTAL BLAST FURNACE OPERATION FOR CO2 ULTIMATE REDUCTION**

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In COURSE50 STEP2, integrated verification tests of the reduction of CO<sub>2</sub> emissions and CO<sub>2</sub> separation from the blast furnace are being conducted, using a newly build 12 m<sup>3</sup> experimental blast furnace and a 30-t-CO<sub>2</sub>/day chemical absorption process evaluation plant simultaneously. Tests have been carried out with the experimental blast furnace to establish a reaction-controlling technology to reduce CO<sub>2</sub> emissions from blast furnaces, using hydrogen-based reductants effectively. The aim of this technology is to increase the hydrogen reduction rate by about 10% and to decrease the direct reduction rate by about 10% compared to conventional operations. The results of the experimental blast furnace operation showed positive effect of the reaction-controlling technology on CO<sub>2</sub> emissions reduction.

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## **CALCULATION MODEL FOR CONCENTRATION OF QUATERNARY SLAG SYSTEM $SiO_2-CAO-AL_2O_3-FEO$**

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**Abstract:** According to the coexistence theory of slag structure, a calculation model of concentration of SiO<sub>2</sub>-CaO-Al<sub>2</sub>O<sub>3</sub>-FeO of depleted copper slag was established. The model was used to calculate and analyze the effects of slag composition, temperature (T) and basicity (B) on the activity of FeO (NFeO). The results show that NFeO tends to increase and then decrease with the increase of basicity, due to the fact that CaO is easier to combine with SiO<sub>2</sub> than FeO to form calcium silicate, which replaces FeO in 2FeO·SiO<sub>2</sub> and increases NFeO. However, an increase of CaO content leads to the formation of high-viscosity silicate 2CaO·SiO<sub>2</sub>, which increases the difficulty of combining CaO with 2FeO·SiO<sub>2</sub> and decreases the NFeO. In the temperature range of 1523-1773K, NFeO decreases with an increase of temperature. In addition, the activity of FeO decreases with the increase of Al<sub>2</sub>O<sub>3</sub> content. By comparing with the measured values, it is found that the calculated results of this model are close to the actual values, and therefore, it can be used as a theoretical basis to guide the carbon carbothermal reduction of copper slag. **Keywords:** Quaternary slag system of SiO<sub>2</sub>-CaO-Al<sub>2</sub>O<sub>3</sub>-FeO; Calculation model of concentration; Activity of FeO

**Sintering / 221**

## RECENT PROGRESS IN IRON ORE SINTERING TECHNOLOGIES IN ANSTEEL

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For raising sinter productivity and quality while reducing energy consumption and raw material cost, a new blending method has been created in Ansteel to optimise sintering blends. Traditionally the granulation of sintering blends in Ansteel has been adopted in disc pelletisers, which was recently found to be one of the causes to unstable blast furnace operation due to their low mixing efficiency. Based on above findings, a number of technical innovations at Sintering workshop 3 were conducted to replace its sixteen existing disc pelletisers with one drum granulator. This experience provided valuable data for optimization of sintering process in Ansteel and even in China. In addition, the single lattice method is proposed to improve the particle-size distribution of coke breeze for sinter quality and lower fuel consumption. Considering the negative impact of high MgO content to blast furnace operations, low MgO sintering was, for the first time, proposed in Ansteel, which has significantly reduced the MgO content of blast furnace slag. Efforts have also been made in Ansteel to further optimize the technological parameters in the sintering process such as the changes of basicity and FeO content. Given the international trend on increasing the bed depth, Ansteel has successfully achieved a bed depth of 750 mm or more in case of 75% concentrates. Finally, the perspective of iron ore sintering is discussed in the paper.

**Blast furnace ironmaking / 222**

## DEVELOPMENT OF THE BLAST FURNACE PRODUCTION IN RUSSIA

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Increase in blast furnace useful volume in course of reconstruction projects and increase in intensity of furnace operation is the major trends in hot metal production in Russian Federation. In majority of furnace enlargement projects the supporting structure, furnace foundation and part of the infrastructure remains the same, while furnace proper is completely replaced with installation of the following new modern systems: furnace shell, furnace cooling system comprised from combination of copper staves, plates and cast iron staves, bell-less top charging devices, high



temperature stoves, gas cleaning and aspiration systems, PCI, oxygen and natural gas injection, slag granulation system, modern control and expert system etc. The sinter and coke quality in industry gradually improves and more and better pellets are used in the metallic burden of blast furnace. As the result during last five years the number of blast furnaces in Russia decreases while hot metal production was increased. Although reconstruction of existing blast furnaces is a major way of improvement in production of hot metal, several new blast furnaces are recent built: “Rossiyanka “ (BF7) at NLMK, BF 7 at NTMK-Evraz and BF #2 at Sukhaya Gora Iron & Steel Works. As the result of these changes many blast furnaces in Russia, for example BF 7 “Rossiyanka” at NLMK, BF 1, 2 CherMK, BF 5 and 6 at NTMK-Evraz operate with World highest specific productivity (3.5-3.7 thm/m<sup>3</sup>/day) and low total fuel and coke rates, while using only domestic coals and iron ore.

**Direct reduction / 223**

## **DIRECT REDUCTION: TRANSITION FROM NATURAL GAS TO HYDROGEN?**

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The future of the European steel industry demands solutions for carbon free production routes to fulfil the challenging goals of today’s climate policies. In terms of CO<sub>2</sub>-emissions, the reduction process is the most relevant process – be it in a blast furnace or in a direct reduction plant. One solution to this issue could be the transition from fossil-based to hydrogen-based reduction of iron ore. If the hydrogen is produced with electrolyzers by means of renewable energies, the new process would be free of carbon dioxide.

In a cooperation of the Hamburg University of Applied Science (Department of Process Engineering) and ArcelorMittal Hamburg, a concept of a new hydrogen-based process is evaluated. ArcelorMittal Hamburg operates the only direct reduction plant in Western Europe, which uses already up to 60% of hydrogen for the reduction of iron ore. It thus has a deep process understanding and experience in low-CO<sub>2</sub>-reduction of iron ore. For the development of a new process, a concept study was conducted with in-house simulation tools. The results show the energy-demand to be in the same range as for today’s direct reduction process. Nevertheless, the energy has to be delivered by renewable energies, which will lead to much higher costs compared to natural gas. Though the transition from natural gas to hydrogen is possible from a technical point of view, there are big obstacles concerning the economics of such a new process. The investment costs as well as the operating costs for such a new plant would be much higher than those of a conventional process. On the other hand, the hydrogen-based process has to be tested in a pilot plant to show “proof of concept”, for which ArcelorMittal Hamburg would be the ideal location.

**Blast furnace ironmaking / 224**

## **THE CONCEPT OF CHARGING DIFFERENT SINTER SIZE FRACTIONS INTO THE BLAST FURNACE**

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In sinter plants, at the end of the sintering process the product is subjected to high performance screens of 20 mm, 10 mm and 5 mm respectively. This allows part of the middle size fraction to be utilized as a hearth layer in sinter strands. Normally, the screened product is then remixed to

be sent to the blast furnace plant, where it is charged into the furnace. In contrast, if the screened material is charged in separate layers in the BF, the overall pressure drop may be decreased, as narrow material distribution results lower pressure drop. In order to verify the concept a set of pressure drop experiments were carried out for each of the different size fractions and coke particle layers along with the combination thereof. In this paper, the results from the experiments are discussed along with a discussion on the implication of such a charging process on blast furnace operation.

**Environmental control in coke and ironmaking / 225**

## **BFG DRY DEDUSTING SYSTEM AT POSCO GWANGYANG NO.1 BF**

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Gwangyang No.1 blast furnace blown in 2013 with 6,000 [U+33A5] inner volume (first half in 2017, Po 2.36t/d/[U+33A5], RR 488.0kg/t-p), and dry-type dedusting system is installed at that time. The introduction background is electricity cost saving through TRT power generation and reducing the amount of waste water discharge, compared with wet-type dedusting system. The dedusting system of Gwangyang No.1 BF is consisted of 18 chambers and 240 bag filters. And there is also wet-type dedusting system (bischhoff scrubber) in case of emergency. Compared with No.2~5 BF, the power generation has increased and the amount of waste water discharge is 10~20%. The following issues have arisen during operation, and improvement activities are in progress. (1) [Problem] There was clogging bag filter and corrosion of TRT with dust sticking. [Solution] Prevention dust sticking by using steam heating and improving facilities (2) [Problem] Dust can not be transported by vehicle because of high temperature and smoke. [Solution] We changed the method of emitting dust and add the process of lowering the dust temperature. In result, compared with initial operation, TRT power generation (40.2→46.0kwh/t-p) and operation efficiency ( $\eta_{CO}$  46.8→48.8%) have increased in recent. Considering the overall economic feasibility, there is an economic merit.

**Postersession and Coffee Break / 226**

## **THE RELINING OF POHANG NO.3 BLAST FURNACE**

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Pohang No.3 BF has been repaired it from February 24th to June 6th for 102 days. POSCO intend to improve operation efficiency and save costs by enlarging inner volume from 4,350 to 5,600m<sup>3</sup>. The relining criterion are that remaining of hearth refractory, wear of body shell, needs for increasing production and so on. Recently, the most critical point among them is the remaining of hearth refractory considered minimum remaining is 600mm. Although, the remaining of Pohang No.3BF hearth refractory is about 900mm, relining was needed for wear of body shell by high productivity.

The strategies for extending blast furnace campaign life are described. First, switching body cooling system. The body cooling system is changed from copper stove to dense cooling plate which was adopted design criteria for the thermal and mechanical wear mechanism and applied same to Gwangyang No.1BF and Pohang No.2BF. POSCO's design concept could be minimize the wear of the blast furnace even at the high productivity. Second, the improvement of main shell profile. The main shell profile was changed belly, throat, hearth diameter, bosh and shaft angle, inner volume and so on. Last, change in refractory design. According to the heat load of furnace body, refractory design was adopted to maximize the cooling ability and minimize

the cost. In addition, the design of the refractory block of tap hole was changed from 3block to 2block in order to prevent leaking of the molten Iron.

In addition, new measuring instrument were installed in the blast furnace proper to monitor the gas distribution, segregation fines distribution and deformation of body shell. First, We installed Acoustic gas temperature measurement system that monitor the circumferential distribution of gas flow inside the Blast Furnace. We can change the charging mode using that system. Second, We installed Profilemeter. Profilemeter can measure the segregation fines distribution according to the charging mode. Finally, FBG sensor was installed that check the crack on Hearth Shell. Also it is possible to manage to melting iron level.

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### PETROLOGICAL STUDY OF SINTER-PELLET-COKE INTERACTION IN ADVANCED SOFTENING AND MELTING (ASAM) EXPERIMENTS

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Advanced Softening and Melting (ASAM) experiments were performed with mixed sinter-pellet burdens of contrasting compositions, showing large differences in vertical contraction and pressure-drop curves (vs T, time). To understand the mechanisms behind these differences, experiments were interrupted at key stages of the simulated BF trajectory for detailed petrological investigation. Combining multi-scale structural and chemical (micro-)analysis with thermodynamic calculations in Factsage helps explain the contrasting ASAM results in terms of chemical interaction between sinter and pellets within the ferrous layer, and the processes of metal-slag-solid oxide segregation at the ferrous layer's margins adjacent the coke layer and graphite crucible.

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### THE POSSIBILITY OF SIGNIFICANT BF-HEARTH LINING LIFE EXTENSION

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Significant Blast Furnace (BF) hearth lining life extension is the target of the improved BF-hearth lining observation management; provided by Paul Wurth, Germany, (PWDE).

The hearth lining main property modifications occur noteless during the running BF-life campaign and influenced the real hearth lining wear profile.

No classical hearth lining temperature and heat flux observation implementation can detect the main physical and chemical property modifications and their alterations during the running BF-campaign.

A number of main measuring disadvantages and poor evaluation results prevents up to this day the necessary true hearth lining wear profile calculation. For example: • Supply of insufficient hearth lining temperature and heat flux data; • Formations of „heat resistances“, like joints, slots, gaps, structure transformations, embrittlements, like „brittle layers“; • Particular variations of the lining grades TC-values and their alterations during the running BF-campaign.

It is very noticeable, that the classical measured value disadvantages and ist poor evaluation results take place already in an early stage of the running BF-campaign. The real hearth lining weak points, like accelerated wear, „hot spots“ or critical reduced hearth lining thickness, can't detect in an early stage for appropriate counter measurements.

PWDE has developed and improved in the last decade precise multipoint temperature & heat flux sensor Probes, (MTP-sensor probes). Meanwhile, the well experienced tool is implemented in a number of BF-hearth bottom and side walls, recording excellent performance data results. The new developed chilling device, necessary for safety pilot core probe drillings and core probe extractions in the BF-hearth lining without salamander tapping will be introduced in this paper. The paper highlights the well experienced hearth lining measuring tool (MTP- sensor probe) for an improved lining observation, true lining wear forecasts and an extended BF-hearth lining life campaign; in spite of „heat resistances“ and / or „brittle layer“ formations in the BF-hearth lining.

**Blast furnace ironmaking / 230**

## ESTIMATION OF LIQUID LEVELS IN THE BF HEARTH

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A well operating hearth is a prerequisite for stable and effective blast furnace operation. On-line estimation of the liquid levels in the blast furnace hearth provides an effective means to prevent disturbances and to improve tap management. A mathematical model of the iron and slag levels in the hearth has been developed. The model is based on mass balances using information about the in- and outgoing flows, hearth geometry and dead-man state. Due to measurement errors the estimated liquid levels exhibit drift and must therefore be periodically corrected. The liquid levels also strongly depend on whether the dead man sits or floats. These aspects are considered in the model. Furthermore, regions with lower dead man permeability in the hearth are taken into account by conceptually dividing the hearth into different pools with cross-communication defined by parametric expressions. The paper first presents the model assumptions and equations, followed by some results from a study where it has been applied to data from a blast furnace. Finally an attempt is made to verify the results by using indirect measurements from the process.

**Sintering / 231**

## ESTABLISHMENT OF NEW SINTERING REGIME FOR HIGH ALUMINA IRON ORE FINES AT TATA STEEL JAMSHEDPUR

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Pellets were introduced into the Blast furnaces at Tata Steel Jamshedpur post the commissioning of pellet plant in the year 2012. The new burden mix (sinter, ore and pellet) offered an opportunity to produce sinter using a new flux regime which permitted flexibility in ore mix and resulted in change of sinter properties. A strategic decision was taken to produce pellets at acidic/minimum flux regime implying that major portion of the flux requirements of blast furnace would be met through sinter. The major shift in sinter chemistry was the increase in CaO content in sinter to >12% based on proportion of sinter and pellet in burden mix in the blast furnace. Simultaneously, fine ore mix to sintering was switched over from higher fines from Noamundi source to higher fines from Joda source. Joda ore fines has lesser amount of super-fines size (-0.15 mm) in granulometry and lesser goethite content in lattice structure compared to Noamundi ore fines. These key strategic changes to operate sinter making in new high flux regime and higher use of Joda ore

finer resulted in improvement of sinter quality parameters like Reduction degradation index (RDI) and Reducibility index (RI) as well as 15% (approx.) reduction in fuel rate for sintering. The improved sinter properties were correlated with presence of higher amount of calcium ferrites and Silico ferrites of calcium and alumina (SFCA) phases in matrix of sinter microstructure.

**Keynote / 234**

## FOOTPRINTS FOR THE FUTURE OF COMMERCIAL FINEX PLANTS

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FINEX® is an alternative iron making process to the blast furnace (BF) route and it is based on the direct use of iron ore fines and non-coking coal, which gives operational flexibility, cost competitiveness and environmental benefits compared to the conventional BF route. Continuous improvements are carried out to increase the process efficiency, including the latest developments of the energy recovery system, changing binders for coal briquettes and the increased production of the hot compacted iron system. Economical benefits are steadily enhanced by the increased use of raw materials with low quality and the recycling of various by-products. The CO<sub>2</sub> removal system working as CCS (carbon capture and storage) in the process brightens the environmental potential. As the core facilities in Pohang Works, two commercial FINEX® plants have already produced over 20 million tons of hot metal and the experience of more than 10 years of commercial operation on the brown field convinces that the equivalent performance will be achieved on green fields. Continuous progress of the FINEX® process promises that the alternative iron making process is now sufficiently competitive with the traditional blast furnace process.

**Blast furnace ironmaking / 236**

## HIGH PELLETS RATIO BURDEN IN HBIS SERBIA BLAST FURNACE

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HBIS GROUP Serbia Iron & Steel is integral Steel plant owned by the HBIS Group that in its composition has 2 Blast furnaces and 3 lines for sinter production. Usual ore burden of the blast furnace is: 35% sinter + 62% pellets + 3% B-scrap. During January and February 2016, test periods were performed at the Blast Furnace 1, where the ratio of the sinter was gradually reduced to final excluding. Each of these periods wasn't lasting for less than 4-5 days. During all test periods, furnace has not any production issues and productivity was improved. Goal of each test period was to determine and compare technology and economy parameters of the Blast Furnace operation. Usage of 100% pellets in the BF ore burden is not usual practice in Europe. This test period is conducted from 20 to 31 January 2016. During the test period were monitored main technical parameters: slag volume and slag basicity, %Fe in the ore burden, usage of fluxes (limestone, quarcite and dolomite), furnace efficiency (EtaCO), total fuel consumption, thermal condition of the blast furnace, cooling system, temperature of BF gases. During this test period, thermal condition of Blast Furnace was normal, without cooling system elements heat overloading. Consumption of fuel was usual or lower. Aimed amount of slag, and basicity was achieved by the usage of fluxes. BF gas utilization was excellent. There were no any irregularities in the Blast Furnace operation. With this is confirmed that Blast Furnace can operate by using 100 % pellets in the burden. During the test period the production cost of the hot metal would be more favorable compared to usual ore burden.

**Environmental control in coke and ironmaking / 239****ILTEC – HIGHLIGHTING POTENTIALS AND ELIMINATING CONCERNS REGARDING THE SAFE AND WATER-FREE COOLING TECHNOLOGY**Dr. HANEL, Martina<sup>1</sup> ; Dr. FILZWIESER, Andreas<sup>2</sup> ; Dr. DEGEL, Rolf<sup>3</sup><sup>1</sup> *Mettop GmbH*<sup>2</sup> *Mettop GmbH/PolyMet Solutions GmbH*<sup>3</sup> *PolyMet Solutions GmbH/SMS group GmbH***Corresponding Author(s):** martina.hanel@mettop.com

It is the increasing demand for an economic and cost saving operation mode that requires effective cooling in order to achieve low refractory wear and good furnace lifetime, which is making cooling technology an important aspect of furnace operation. In addition, the requirements for safety are getting more and more into focus. However, the use of water - today's standard cooling medium - has major drawbacks as it can cause problems both during furnace start up and operation, namely hydration problems, corrosion, and explosion. Not to forget the severe personal as well as economical damage in case of a malfunctioning water cooling system. With this new and patented cooling technology ILTEC and the ionic liquid IL-B2001 as the cooling medium, it is possible to realise a water-free cooling solution and therefore the door is wide open to rethink existing and conventional cooling solutions. Furthermore especially in the area of ironmaking, there is also the chance to recover heat from the process in a more efficient way. However, since the technology is novel and unique there are a lot of concerns and doubts regarding safety for plant operators and employees. Although perfectly unsubstantiated, especially the topic of gaseous hydrogen fluoride formation and the handling and transportation is of great interest and concern. The paper is intended to cover both: highlighting the enormous potential of the technology with special focus on ironmaking but also to eliminate concerns mainly caused by rumour and unawareness.

**Modelling and simulation in coke and ironmaking / 242****TOWARDS THE COMPREHENSION OF FERROUS BURDEN SOFTENING AND MELTING PHENOMENA IN BLAST FURNACE – DEVELOPMENT OF A THERMODYNAMIC APPROACH****Author(s):** Mr. FLORES, Ismael<sup>1</sup>**Co-author(s):** Prof. BAGATINI, Maurício<sup>2</sup> ; Prof. LIMA DA SILVA, Aline<sup>2</sup> ; Prof. HECK, Nestor<sup>3</sup><sup>1</sup> *Universidade Federal de Minas Gerais*<sup>2</sup> *Federal University of Minas Gerais*<sup>3</sup> *Federal University of Rio Grande do Sul***Corresponding Author(s):** ismael.flores@ufrgs.br

In the blast furnace, the onset of softening and melting of ferrous burdens give origin to the region known as the cohesive zone, which is critical to process stability and performance. The softening and meltdown temperatures of ferrous burdens are usually accessed by high temperature softening melting (HTSM) apparatus, which can, to some extent, simulate the blast furnace reduction, temperature and mechanical conditions. However, such properties are highly dependent on the formation of eutectic points as well as on the *solidus* and *liquidus* temperatures of the slag phases, whose characteristics cannot be accurately measured during conventional tests. In this regard, the present work evaluates the suitability of computational thermodynamics as a tool for enhancing the comprehension of the ferrous burdens softening and melting phenomena. For that, composition, reduction profile and softening-meltdown properties of a lump ore, a pellet and a super-fluxed sinter (basicity from 0.02 to 2.07) were obtained from literature and used for carrying out thermodynamic calculations. An iterative strategy was adopted to realize equilibrium calculations from 800 to 1550°C, with an incremental step of 10°C, using Gibbs energy minimization principle along with thermodynamic databases from the commercial package FactSage 7.1. The simulation results were used to predict the whole curve of reduction degree as a function of temperature for different ferrous burdens; since reduction degree from thermodynamics is greater than the experimental one, a restriction factor in the available amount of reducing

gas was introduced in the simulation procedure for taking into account kinetic and diffusional constraints in practical reduction process. In this way, the theoretical curve can accurately reproduce the experimental one, and the amount of liquid and solid oxide phases, as well as their compositions, can be known for the whole curve of reduction degree. The conceived methodology for thermodynamic simulation showed potential to improve understanding of the alterations originated from high-temperature reduction and the onset of softening and meltdown process. The chemical composition of liquid slag phase and its proportion to solid oxide phases were accessed in details during the course of reduction. A correlation was established between the calculated temperatures for first and maximum liquid phase formation and the experimental pressure drop profiles recorded for different samples, which could make it possible to estimate the temperature of formation and thickness of cohesive zone. Finally, the differences in behavior between sinter, pellet and lump ore were discussed from a thermodynamic viewpoint.

#### CO2 reduction and energy saving / 243

### STEP WISE MODIFICATIONS TO BF PLANTS FOR PROGRESSIVE CO2 EMISSIONS REDUCTION FROM INTEGRATED STEEL PLANTS

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The iron and steel industry is a source of industrial CO<sub>2</sub> emissions. The BF-BOF route of iron and steel making is considered as the most successful and economic route, hence widely employed for the iron and steel production. To comply with the targets set by the latest “conference of the parties” (COP) for climate change significant additional effort is required to achieve the target CO<sub>2</sub> emission reduction for the steel plants in Europe.

Paul Wurth is employing intensive research and development work in order to assure that the BF-BOF route will be compatible with future environmental and economic environment. In this paper a range of innovative solutions are analysed. The approach followed is a stepwise retrofit based allowing to stretch the required investment over the time according to the effective calendar which will be set by governmental authorities for the CO<sub>2</sub> emissions trade and cap system.

The steps include a more efficient utilization of input carbon to the steel works for the purpose of saving of iron reductant, consideration of reducing agents having a lower CO<sub>2</sub> emission factor, reutilisation of gases for metallurgical purposes, as well as new approaches for substitution of fuel with renewable electrical power. The current study estimates the technical and economic potential of energy saving and CO<sub>2</sub> emission reduction for each step and demonstrates that the BF-BOF route can significantly and effectively contribute to meet the CO<sub>2</sub> reduction targets.

#### Sintering / 244

### IMPACT OF IRON ORE ULTRA-FINES ADDITION ON GRANULATION IN THE SINTERING PROCESS

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Iron and steelmaking industry is in demand to utilize ultra-fine iron ores due to changes in its availability and quality worldwide. Sintering plants are adapting to introduce higher ultra-fines percentage on their mixtures, raising concerns over the cold agglomeration step, critical to maintaining process stability and performance. Sintering bed permeability, granules mechanical

properties and size distribution are keen factors that must be taken into consideration to produce high-quality sinter. The purpose of the present paper was to investigate the influence of ultra-fines addition on the cold agglomeration process and its impacts on the formed granules. Mixtures were composed of sinter feed, lime and different ratios of two different ultra-fine iron ores: natural pellet feed (−0.15mm) and grinded pellet feed (−0.045mm). Initially, maximum moisture capacity for all tested mixtures was determined by a capillary ascension test. Thereafter the mixtures were submitted to granulation experiments on a laboratory scale granulation route. The granules produced were assessed through its size distribution by the Safe Analysis on Frozen Elements (SAFE) method, by its Granulation Index (GI), Degradation Index (DI) by shatter test and bed permeability by Japanese Permeability Unit (JPU). In order to understand the impact of ultra-fines on granulation, microstructure analysis of the granules was performed by optical microscopy. The results showed that the addition of ultra-fines increased the maximum moisture capacity of the mixture. It was also possible to observe the impact of ultra-fines on the granulation index, degradation index and bed permeability of tested samples. Optical microscopy showed different ultra-fines arrangements throughout the granules structure, which points out to different granulation behaviors. The addition of iron ore ultra-fines on the tested mixtures affects the granulation process, which can indicate limitations to its use in industrial setups.

**Blast furnace ironmaking / 246**

## **CHARACTERISATION OF PC CHAR IN RESPECT TO ITS CONSUMPTION IN THE BLAST FURNACE**

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The rising amount of injected through the tuyeres pulverised coal makes increasingly difficult its conversion within the raceway zones despite of numerous measures to improve gasification of coal particles. Unburnt particles can nevertheless be partly consumed outside the raceway by so called secondary conversion reactions. From this point of view, properties of char that leaves the raceway were in the focus of current study. Chars from two coals with the same grain size distribution were produced artificially in a laboratory furnace at pre-defined conditions in order to find out differences in char properties depending on reaction temperature and coal type. Next to chemical composition that revealed among others volatile yield, petrographic properties has been determined using an oil-immersion microscope. All char samples showed complete disappearance of liptinite phases whereas a significant increase of inertinite was determined with increasing reaction temperature. This effect was in correlation with volatile yield. Physical properties showed an extreme increase in specific surface area by transformation of coal to char which was determined using BET analysis. Microscopic analysis showed high porous particle whereas the average particle size remained almost unchanged and bulk density decreased. However, changes of physical properties were only immense in comparison to its parent coal. Activation energy was determined for coals and chars. A correlation of volatile matter and specific surface area could be identified. The artificially produced char was compared with char generated by injection trials using the MIRI plant simulation the raceway conditions.

**Keynote / 252**

## **RECENT RESEARCH [U+FF06] DEVELOPMENT TOPICS OF IRON-MAKING TECHNOLOGIES IN NSSMC**

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The last decade was a turbulent for the steel industry. The reorganization of steel industry across borders has progressed and the increased demand for steel products has made the price of raw materials such as iron ore and metallurgical coal more volatile than ever. Ironmaking technology division in NSSMC has been exposed to global competition and has tried to cope with



these changes and to increase its international competitiveness by developing such technologies as utilization of lower grade raw materials, productivity enhancement, measures for energy conservation and reduction of CO<sub>2</sub> and NO<sub>x</sub> emission and so on. This paper describes the recent progress in ironmaking technologies in NSSMC.

### Blast furnace ironmaking / 253

## STRUCTURAL CHARACTERIZATION OF COKE FROM THE TUYERE REGION OF THE BLAST FURNACE

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Coke, the main fuel of the blast furnace (BF) process, undergoes significant structural changes both in the macro- and microstructural level during its descend through the BF. To investigate some of these properties of coke, samples have been taken by drilling through one of the tuyeres on an actual BF. The aggregate mass has been processed to separate the coke pieces from it. These samples have been characterized using several sophisticated techniques like Raman Spectrometry, BET analysis, X-Ray diffraction etc. The results have been compared to the similar properties of the parent coke. The results from these investigations will not only help us to analyze the changes in the coke structure in a deeper way, but also helps the BF operator to predict its quality during the process, providing in turn the promise of a better operation.

### Recycling of in-plant residues / 254

## CONVERSION OF MILL SCALE WASTE INTO HIGH PURITY PIG IRON SUITABLE FOR DUCTILE CAST IRON PRODUCTION

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In Egypt, the crude steel production has increased significantly with higher growth rate in the past years of the 21st century. Furthermore, many mill steel companies have been established for steel processing. With the increase in steel production and steel processing, a large amount of waste materials (slag, dust and mill scale) are produced. Mill scale is one of these waste materials produced during preheating of steel slabs and billets before hot rolling in all iron and steel companies and its specific production is about 20-40 kg/ ton of hot rolled product. The mill scale generated from the hot rolled steel products in Egyptian integrated and processing steel companies is amounted 200000 tons annually. This bi-product mill scale is mainly iron oxides and considered a rich iron source. On the other hand, high purity pig iron is used in the production of ductile cast iron. Its consumption is about 25% of the produced ductile cast iron. All needs of high purity pig iron for Egyptian industry are imported. This work aims at recycling of mill scale by adjusting smelting process to produce high purity pig iron. Different heats of smelting process were carried out at submerged arc furnace using different reductants and different fluxing materials to adapt an economic smelting process for producing high purity pig iron with minimum Mn, P, S and other impurities and attain the highest recovery and output. By using the optimum condition, high purity pig iron is obtained with chemical composition conforming the requirements to be used in the production of ductile cast iron. The industrial application of the produced high purity pig iron revealed good mechanical properties of the cast

product conforming the requirements of ductile cast iron and the microstructure observation confirmed the obtained mechanical properties.

**Blast furnace ironmaking / 258**

## INCREASING THE EFFICIENCY OF BIOMASS PRODUCT INJECTION INTO THE BLAST FURNACE

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The benefits of biomass usage as renewable energy source and reducing agent in the steel industry, particularly, by its injection into the blast furnace tuyeres is known. This contribution focuses on two aspects, which could increase the economic efficiency of this technology. The first one is related to the thermal treatment of biomass. Woody biomass waste and biomass residues were pyrolysed in a laboratory scale screw continuous reactor at different temperature profiles. Besides charcoal, yields of organic liquid and a gas mixture consisting of carbon oxides, light hydrocarbons and hydrogen were considered. The share and quality of these three fractions can be controlled by the pyrolysis parameters such as temperature, heating rate, residence time or presence of catalysts. The second aspect is related to the optimisation of grain size of injected solids. Different grain size fractions in the range from about 0.1 to 1.8 mm were prepared and tested using a batch injection rig. Furthermore, microstructure of samples were examined. Results were compared with PC. It was concluded that coarser grinding of charcoal than that for coal can be sufficient for its conversion in the blast furnace raceway. The microstructure of charcoals may have a great influence on their conversion behaviour along with the chemistry. The effect of injection rate on conversion rate depends on grain size of charcoal.

**Sintering / 259**

## EVALUATION OF SINTERING BEHAVIOUR OF IRON ORES BASED ON ORE CHARACTERIZATION

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The qualities of iron ores have been deteriorating, which has influenced sinter quality and productivity adversely. In the sintering process, iron ore fines, fluxes such as limestone and coke breeze, are granulated, then charged and fired in a sinter machine. Sinter quality and productivity are strongly affected by the formation of initial sinter melt, assimilation and penetration into nucleus particles by the initial melt, and solidification of sinter melt. Especially, the assimilation degree and penetration depth depend on the characteristics of individual ores. However, the effect of ore mineralogy on these sintering reactions has not yet been studied in details. In this study, a simple evaluation method was proposed using mini-tablets consisting of coarse particles from various iron ore fines as nucleus particles and chemical reagents or iron ore fines as matrix forming materials. Iron ores were selected to represent various textures ranging from dense to porous ore types from Australia and Brazil. Tablets were fired under simulated sintering conditions to investigate the penetration and assimilation behavior of different ore types. The assimilation and pore structure of resultant analogue sinters was also evaluated and the role of ore mineralogical texture was further discussed.

**Blast furnace ironmaking / 260**

## PROPERTIES AND PERFORMANCE OF TAP HOLE CLAYS WITH RESPECT TO STABLE BLAST FURNACE OPERATIONS

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Blast furnace taphole clays can be extremely sophisticated refractory products. The correct selection is affected by several blast furnace operating factors. The complexity of these formulations mirrors the multitude of often conflicting properties and characteristics that are demanded from the modern day taphole clay, e.g. refractory properties, plasticity, erosion stability and the suitability to form a compact leak-proof plug. However, the taphole clay manufacturer not only has to address these 'service' requirements but increasingly there is pressure to meet demanding health and safety as well as environmental standards. The finished product may not look that impressive when stacked on a pallet but this material represents the culmination of significant knowledge and experience in terms of materials technology design. It is our experience that quite often products need to be modified, even custom designed to adapt to a specific furnace or operating practice. Also it is not always the largest furnaces that represent the biggest challenge. We will report about challenges for the complete product chain from raw material selection, production to final application and how to overcome especially operational difficulties.

**Blast furnace ironmaking / 262**

## LKAB EXPERIMENTAL BLAST FURNACE, AN IMPORTANT TOOL IN DEVELOPMENT OF PRODUCTS AND PROCESSES FOR SUSTAINABLE IRONMAKING

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Since LKAB decided to invest in a pilot scale blast furnace in 1996, the equipment has over the years produced a significant amount of data and results for improvement of products and processes within ironmaking. The experimental blast furnace has played a vital role in many research projects, producing important results which simplify the decisions whether to move into larger scale or continue development. The Experimental Blast Furnace has not only been an important tool for LKAB product development but also contributed to the continuous improvements for ironmaking technology. Since the start, various burden materials has been tested together with different types of injection materials. Larger joint projects like ULCOS and Course50 has been developing and testing ideas in pilot scale in order to evaluate possible routes for a more environmentally friendly production. Also individual customer support projects has been conducted where detailed analysis of burdening materials from blast furnace atmosphere has been sampled and evaluated. For the future, the EBF will hopefully continue to be a part in the strive to minimize environmental impact and increase energy efficiency within the field of ironmaking. It will also continue to be a vital part in the development of LKAB high grade products, ensuring that every new product or development is thoroughly tested before being introduced to customers.

**Recycling of in-plant residues / 264**

## EFFECTS OF SLAG CHEMISTRY ON LIQUIDUS TEMPERATURES OF HIGH TITANIA SLAGS

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High temperature experiments have been undertaken using equilibration, quenching and EPMA technique to characterise the phase equilibria of high Ti-containing slag systems. The experimental results have been presented in the form of pseudo-binary sections to show the effects of CaO, TiO<sub>2</sub> and oxygen partial pressure on liquidus temperatures.

The primary phases observed in the composition range investigated include pseudobrookite M<sub>3</sub>O<sub>5</sub> (MgO.2TiO<sub>2</sub> – Al<sub>2</sub>O<sub>3</sub>.TiO<sub>2</sub>), spinel MgO.(Al<sub>3+</sub>,Ti<sub>3+</sub>)<sub>2</sub>O<sub>3</sub>, perovskite CaTiO<sub>3</sub> and rutile TiO<sub>2</sub>. The liquidus temperatures were found to decrease in the TiO<sub>2</sub> and M<sub>3</sub>O<sub>5</sub> primary phase fields with increasing CaO concentration and increase in the spinel and CaTiO<sub>3</sub> primary phase fields with increasing CaO concentration.

The experimentally determined liquidus temperatures were found to be in general significantly higher than those predicted by FactSage model. Experimental data and FactSage predictions show that the liquidus temperatures under reducing conditions are higher than those in air.

## Automation and digitalization in coke and ironmaking / 266

### How laser based element analysis reduces costs, supports stable processes and increases flexibility in modern iron production

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#### 1. Initial situation

In iron making, wet-chemical, spectroscopic and radiometric methods are well established for a long time already. Nonetheless, the industry is struggling with certain shortcomings or disadvantages of these methods and is increasingly asking to overcome such limitations. Some analysis methods are contacting, some may require tedious sample preparation, some are using harmful ionizing radiation, some cannot measure all elements equally, some require a long time until results are available. To make steel production smart a method would be desirable that is universally applicable, provides results continuously, very quick and is easy to use.

That would be too good to be true, would it? Well, as already seen in many other applications, the use of lasers can open up new possibilities.

## 2. New requirements lead to innovative analysis methods

Ever increasing competition and rising demands on timely fault-free shipments of ever smaller lot sizes have already led to continuous process improvements in steel mills, e.g. by use of laser sensors for real-time measurement of physical properties, like thickness, width, flatness, length etc. With those properties being no longer a major concern, tighter control of other material properties is gaining more attention, namely alloy (chemical) composition of feeder materials.

Tackling the challenge of inconsistent raw materials quality in iron making due to global sourcing of input materials, has also increased the need of continuous monitoring of feeding materials. Input streams that need to be analysed permanently are: - the calorific value and acidity, - the ash percentage - the sulphur and volatile contents of coal - the swelling of coal when coking, - the iron content in the iron ore - the basicity of iron ore - the variety of elements introduced by scrap recycling. - ...

By knowing what material quality is on hand, corrective action can be taken by targeted addition of deficient elements before or while charging, or by rejection of certain other material batches.

## 3. Applicable applications for LIBS based smart process control

Analysis of the elemental composition is required or desirable in multiple steps and locations of steel making and steel rolling.

Let's have a look at some typical iron industry applications requiring elemental analysis to judge how close this technology can come to above mentioned ideal for the metals industry.

1. Continuous monitoring of the raw feeder materials like coal, coke, limestone, iron ore, scrap metals, sinter etc. on conveyors for charging control of sinter plants, blast furnaces and electric arc furnaces
2. Analysis of the slag composition at furnaces and converters, in solidified or even hot liquid state.
3. Analysis of the composition of steel samples, in solidified or even hot liquid state
4. Identification of alloy changes at the cooling bed exit, especially for SBQ mills, for proper allocation of all partial lengths to the initial billet and rolling order
5. Identification of alloy changes at the end of the (cold) finishing line for proper allocation of each individual rod to the proper shipment batch according to the production schedule
6. Analysis and sorting of head, tail and cobble croppings for alloy-true remelting of internal scrap, avoiding contamination of melts with unwanted elements.
7. 100% material identification at the charging side of reheat furnaces to ensure proper loading according to the production scheduling
8. 100% material identification after de-scaling to ensure proper alloy scheduling at the rolling train entrance.

### 3.1 Applicable applications –LIBS on the feeding side

Production of the desired steel grade according to Industry 4.0 smart and in the shortest amount of time already begins when charging the (blast or EAF) furnace: Is the proper mix of materials fed to the furnace at the right time, in the right amount? LIBS sensors installed at the charging side allow precise identification and quantification of the currently charged materials, e.g. to avoid charging copper or other detrimental elements, to prevent mishaps in the charging sequence, as well as to charge fluxes in the right composition and basicity range. By ensuring charging of all required elements in the optimum mixture, time consuming analysis and correction phases in the smelting process can be reduced, thus improving the utilization significantly.

### 3.2 Applicable applications –LIBS in the melt shop

In melt shops, two different measuring methods are commonly in use. One system is to analyse iron and another one is to analyse slags. With LIBS, just one system can do it all.

In smelting and in ladle metallurgy, LIBS sensors can precisely determine the composition of slag and metal in real-time because they can measure in hot liquid state already. Thus time-delays incurred by conventional analysis methods requiring cooled down solid samples as well as tedious sample preparation are eliminated. E.g. the optimum tapping point can be determined with continuous monitoring of the iron oxide content in the slag almost to the second

Providing immediate results LIBS allows the production process to meet the target slag and alloy compositions much quicker. Hence in these process steps, not only utilization, but also yield can be improved by using LIBS analysis.

### 3.3 Applicable applications –LIBS in the milling, rolling and processing lines

Further downstream, Positive Material Identification (PMI) by LIBS sensors in rolling mills and processing line, starting at the reheat furnace entry, down to the finishing line exit, helps all mills dealing with frequent alloy changes. For this purpose, FiberLIBS Inline systems with a compact, separate sensor head, mounted at a suitable location of the respective conveyor system, are the ideal solution.

Automatically measuring the composition of each work piece as it passes by on the conveyor, and comparing it against the alloy specification given in the production schedule, detects deviations or confusions immediately. By not only eliminating material confusion, but also allowing to cut down on gaps in the rolling sequence (which now seem to be the common practice to keep different alloys separate) mill utilization can be improved, and costly complaints and rejects due to confused alloys can be avoided.

In times of increasing flexibility requirements PMI is a significant improvement especially for SBQ producers dealing with highly customized products.

### 3.4 Applicable applications – LIBS in the laboratory

Last not least, also in metallurgy labs, LIBS systems can help to increase throughput of sample measurements. It can also solve demanding analysis tasks, like penetration of refractories by alloy elements, fast measurement of segregation effects and patterns in metal samples of almost any size, analysis of even smallest inclusions in metal samples, and so forth. LIBS capabilities Compared to other OES (optical emission spectroscopy) methods LIBS can:

- Analyse all known elements, regardless of their atomic weight. There is no limitation regarding „light“ elements.
- Electrically conductive as well as nonconductive materials can be analysed.
- LIBS analysis can be carried out from a distance without any physical contact
- The analysis is very fast, with precise results available within milliseconds
- The measurements can be carried out at a high repetition rate up into the kHz range, making it ideally suitable for moving parts with velocities up to 3 m/s and more
- Due to the very small spot size, the LIBS method provides a very good spatial resolution, which helps especially with the analysis of elemental distribution of heterogeneous materials.
- In LIBS spectroscopy, no harmful ionizing radiation is present.
- LIBS analysis typically does not require any material preparation, but can be carried out without sampling directly in the regular production material flow

## 4. How does LIBS work?

A high-energy laser pulse of very short duration (typically 1 to 40 mJ, 1 to 100 ns duration) is focused on the surface of the material to be inspected, generating a plasma fume of the material surface. In this process, some material is ablated, generating a „crater“ of 15 nm to 5µm depth and 20 to 100 µm diameter, depending on the parameters of the laser in use. Upon recombination

of the plasma (also called breakdown), the electrons falling back on their original orbits emit photons (normally visible as light flash) with wavelengths characteristic for the specific elements. („spectral finger print“) A high-resolution spectral analysis of the emitted light (in NIR, VIS and UV, depending on the respective elements) with chemometric methods does not only allow to identify which elements are present, but also a fairly precise computation of their relative amounts.

## 5. Industry proven even in harsh environments

The long stand-off distance, combined with a very fast autofocus system of the MineralLIBS, allows the installation in a safe distance above conveyors, measuring on the unconditioned regular material stream. Due to the high measuring frequency and the small spot size, even small impurity events in the measurement track of the material flow can be registered.

## 6. Summary

LIBS is a versatile measurement method addressing current needs and challenges of a globalized world regarding analysis of elemental composition in the metals industries. It has a big potential for improvements of yield and utilization in multiple stages of the production processes, thus enabling metal producers and processors to reduce secondary processing (e.g. waiting) times as well as sourcing costs. In addition LIBS helps to increase process stability and product quality.

### Smelting reduction / 267

## PREDICTION OF PHASE TRANSFORMATION AND VOLUME VARIATION PREDICTION OF HEMATITE ORE PARTICLES DURING IN-FLIGHT MELTING AND REDUCTION

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Hisarna is an emerging and promising alternative ironmaking process. Smelting cyclone is used to melt and pre-reduce fine and un-agglomerated iron ore particles in Hisarna reactor. Fine ore and flux are injected in the smelting cyclone together with oxygen. The injected ore is intensely mixed with rising hot reducing gases, undergoes partial reduction and melting. The melt hits the water-cooled sidewalls of the cyclone section and flows down along with the wall and into the liquid bath in the smelting reduction vessel (SRV) where the final reduction takes place. The ore in the cyclone section is pre-reduced to a degree of about 20% through thermal decomposition and reduction by the SRV gas. The temperature of the melt is approximately 1450 °C. Variation of ore particles' state is difficult to observe inside the cyclone. Therefore, theoretical estimation is extremely important under these conditions. Phase transformation is an essential information for reaction analysis. In addition, density of particles is necessary to estimate the residence time of particles in the cyclone. They were investigated in this study. Phase transformation of iron particles were experimentally studied in simulating cyclone conditions and compared with thermodynamic calculation results. During the reaction process, mineralogy of iron ore particles transforms from hematite to sub-oxides sequentially. The density of particles can be predicted in the reduction based on the phase composition. Therefore, previous density models were evaluated with reported experimental data of slag. As a result, a suitable density model has been developed to calculate the density of slag mainly with FeO-Fe<sub>2</sub>O<sub>3</sub> contained. Density of the reduced ore particles was estimated based on this model. The results show that reduction of the ore could lead to about 10 % shrinkage of the particles. On the contrary, melting contributes around 10 % swelling of the ore particles. It would result corresponding variation of reaction time in flight.

**Modelling and simulation in coke and ironmaking / 269****SIMULATION RESEARCH ON IMPROVING 7.63M COKE OVEN HIGH-HEATING UNIFORMITY IN SHOUGANG****Author(s):** Mr. MA, Chao<sup>1</sup>**Co-author(s):** Mr. XUE, Limin<sup>1</sup>; Mr. YAN, LiQiang<sup>2</sup>; Mr. ZHOU, jiliang<sup>3</sup>; Dr. ZHANG, dianwei<sup>4</sup><sup>1</sup> *Shougang Group*<sup>2</sup> *Shanxi Coking Company of Tangshan Shougang Jingtang*<sup>3</sup> *ShouGang Group*<sup>4</sup> *shougang group***Corresponding Author(s):** superchao1986@126.com

Combustion processes of heating gas for 7.63m coke oven in Shougang were simulated by the adoption of CFD modeling. Through calculation and analysis, the following conclusions were obtained: (1) As the heating gas flow rate decreased, the average velocity of gas inside the combustion chamber was reduced; (2) When the gas flow rate in the vertical flue was reduced by 5m<sup>3</sup>/h, the average temperature in the combustion chamber was decreased by 0.55 [U+2103] and the maximum temperature was decreased by 1 [U+2103]. It meant reducing the gas flow rate in the vertical flue by 5m<sup>3</sup>/h had little effect on the overall oven temperature. (3) The reverse operation of gas can increase the internal temperature of the combustion chamber. (4) Increasing the air flow rate at the bottom of the vertical flue, meanwhile, reducing the air flow rate in the middle and upper part can obviously increase the average temperature of the combustion chamber, decrease the maximum temperature and improve the uniformity of the overall oven temperature.

**Modelling and simulation in coke and ironmaking / 270****STRATEGIC OPERATION AND RAW MATERIALS PLANNING FOR INTEGRATED STEEL PLANTS IN THE PROCESS INTEGRATION PLATFORM m.simtop****Author(s):** Dr. WEISS, Bernd<sup>1</sup>**Co-author(s):** Mr. SPANLANG, Andreas<sup>2</sup>; Dr. WUKOVITS, Walter<sup>3</sup><sup>1</sup> *Primetals Technologies GmbH*<sup>2</sup> *K1Met GmbH*<sup>3</sup> *TU Vienna***Corresponding Author(s):** bernd.weiss@primetals.com

Iron and steel making requires a wide range of different raw materials significantly influencing process performance which demands a continuous optimization of process routes also with respect to energy efficiency as well as environmental emissions. Steadily changing raw material prices and qualities, market situations and product variations are challenging integrated steel plant operators in production planning and cost optimization. Primetals decided to develop a comprehensive metallurgical flow sheet model library for simulation and optimization of integrated steel plants. Intensive development efforts were taken in order to migrate existing well established calculation and engineering routines as well as integrate newly developed models. The generated model library enables the setup of mass and energy balances for integrated steel plants, development and evaluation of new process concepts as well as investigations on impacts of raw material changes and trace material distributions. By using this process integration platform, it is possible to compare different iron and steelmaking routes within one standardized environment. In this publication an insight will be given on the competence of mSIMTOP in depicting integrated steel plant operation, enhance raw material planning, show the effect of new raw materials and new internal recycles on realistic examples.

**CO2 reduction and energy saving / 271**



## ENERGY EFFICIENT AND LOW EMISSION SINTER COOLING

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Cooling of hot sinter involves the release of significant quantities of energy and is a source of fugitive dust emissions. The increasing pressure that steel producers are facing in regard to energy consumption, reduction of CO<sub>2</sub> and air emissions, require new processes and technologies to maximise energy recovery of the sinter cooling and to lower its environmental impact. Paul Wurth has been working intensively on the improvement and redesign of sinter coolers and recently finished developing a new type of shaft cooler based on the counter-flow principle, resulting in advanced thermal efficiency and energy recovery rate.

In parallel, the higher amount of energy recovered from the sinter cooling allows boosting the efficiency of the processes that reuse this energy. Examples are the partial recirculation of hot air to ignition hood and/or the sinter strand and the generation of steam that may be combined to the production of electricity. An interesting alternative is to use the steam for driving a turbine which is coupled directly to the main fan, a setup which increases the yield of thermal energy conversion even further. In this regard, Paul Wurth recently joined hands with a renowned turbine manufacturer to be able to propose complete heat recovery solutions specifically adapted to each customer's requirements.

As the new cooler is based on the suction of cooling air through the bed of hot sinter, dust emissions are strongly reduced compared to existing sinter coolers, making this technology fit for upcoming reinforced legislations on dust emissions.

With a very small footprint, the new cooler can be retrofitted in most existing plants even with reduced available space or it can be implemented in greenfield projects in order to reduce the overall plant footprint.

Cokemaking / 272

## MICROSTRUCTURAL EVOLUTION OF BLAST FURNACE COKE DURING EXPERIMENTAL HEATING – THE IFORS APPROACH

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Furnace coke was experimental heated between 850°C and 1100°C by varying the gas composition and the alkali content of the raw coke. Raman spectroscopy (Iterative Fitting of Raman Spectra) evaluates the microstructural change of coke during the experiments. The obtained results indicate a significant microstructural variation within a bulk sample. This variation controls significantly the coke quality as estimated from standard experiments (CRI 23.9 - 38.3). A bulk sample with a CRI value <30 is composed dominantly of lumps showing a relatively low structural ordering. During experimental heating, the structural ordering of such lumps increases. A bulk sample with a CRI value >30 is composed dominantly of lumps showing a relatively high structural ordering. During experimental heating, the structural state of such lumps remains unchanged unless a strong reaction is induced by adding alkaline elements. It is suggested that under laboratory conditions, thermal and chemical energy, affecting a microstructurally low-ordered coke, first reorganizes the structural state of the individual coke lumps, retarding the onset of the Boudouard Reaction.

**Environmental control in coke and ironmaking / 273****NEW EFFICIENCY IN IRONMAKING FACILITIES****Author(s):** Mr. STEINWANDTER, Andreas<sup>1</sup>**Co-author(s):** Mr. BRUNNER, Christian<sup>2</sup>; Mr. VARGA, Andras<sup>2</sup><sup>1</sup> *Primetals Technology Austria GmbH*<sup>2</sup> *Primetals Technologies Austria GmbH***Corresponding Author(s):** andreas.steinwandter@primetals.com

The demand for increasing energy efficiency is one of the global megatrends of our time. Although the steel industry suffers from a volatile economic environment, steel plant operators are interested to find opportunities for sustainable cost reduction. Steel mills are trying to cut electrical power and energy costs as these are among the biggest cost factors that can be influenced. The product cooler of sinter plants offers an excellent possibility to recover up to 50 - 80 kWh thermal energy per ton of sinter by using either a steam or hot water boiler. The recovered energy can be used to produce electrical energy or be used for instance for the SCR (Selective Catalytic Reduction) – Technology, which is applied to reduce the nitrous oxides in the primary sinter off-gas in conjunction with Primetals' MEROS® technology. The SCR technology requires typically an elevated reaction temperature and can be therefore an efficient consumer for the generated waste heat and contributes to the efficient gas cleaning of the sinter off gas. Furthermore significant proportion of the generated blast furnace (top-) gas with the inherent pressure/thermal energy is unutilized since the blast furnace gas is just throttled by means a throttling element to reach the pressure of low pressure gas network. In order to recover this energy, Primetals Technologies offers its TRT (Top-Gas Recovery Turbine) solution that includes a gas expander and the required auxiliaries downstream of a widely used wet or innovative dry dedusting technology (MERIM®). In the energy generation process from blast furnace gas approximately 30 – 40 kWh of electrical energy per ton of hot metal is possible with low maintenance costs. This electricity can be used for internal usage within the steelworks or for external sales to the power grid thereby reducing CO<sub>2</sub> emissions. One of the global trends that are constantly challenging the iron and steel industry is related to the generation of fines, slurry, sludge and scales, summed up as ferrous by-products. The recycling of those by-products is commonly practiced in many steel plants. These materials normally cannot be used directly in the primary processes. The most common application is to add ferrous by-products which are suitable concerning chemical composition and grain size distribution to the sinter mix. Primetals will present latest developments in the field of cold briquetting of ferrous by-products and of coal briquetting. Giving examples and results of executed project(s) of cold briquettes directly fed to the DR shaft, and other solutions for integrated steel mills. Coal briquetting on the other hand is based on coal fines which often originate from wear during coal transport from mine to plant. These fines can be used to produce briquettes designed either for the use in a smelting reduction process (COREX®/FINEX®) or for enhanced coke oven operation in the traditional blast furnace route.

**Cokemaking / 274****DEVELOPMENT OF LOW THERMAL EXPANSION SILICA BRICKS FOR COKE OVEN****Author(s):** Mr. PRASAD, Birendra<sup>1</sup>**Co-author(s):** Mr. PANDA, Bharati Krushna<sup>1</sup>; Mr. GRUBER, Ingo<sup>1</sup>; Mr. SWAIN, Suvash Chandra<sup>1</sup><sup>1</sup> *DALMIA OCL***Corresponding Author(s):** prasad.birendra@dalmiaoel.com

Silica Bricks are made from Quartzite which mostly contents quartz phase. During making, the quartz is converted into phases like Tridymite and Cristobalite along with some amorphous phases. This polymorphic transformation in Silica brick is governed by the impurities present in parent quartzite and also with the addition of mineralizers. However in this process very little amount (<1%) of quartz may remain unaltered. The behaviour/ properties of silica bricks is governed by its physical properties (AP/BD/CCS), thermal and thermo-mechanical properties. Out of these, thermal expansion is considered to be one of the major criterion. Thermal expansion plays a vital role in designing and lining of coke ovens. Consistency in thermal expansion of silica

bricks is controlled by the quantity of different phases (Tridymite, Cristobalite, Residual quartz etc) present in bricks. In our conventional silica bricks the thermal expansion ranges between 1.28-1.34% at 1000 deg C and these bricks are widely used in Indian coke ovens in normal and tall batteries. Extensive research has been carried out in Dalmia-OCL to develop low thermal expansion bricks ranging between 1.12 -1.25% by controlling the mineralogical phases during manufacturing with available quartzite. In this paper the authors are trying to highlight how the thermal expansion of silica bricks can be reduced by increasing Tridymite content in the brick and then how content of Tridymite formation is linked with the composition and production process like chemistry of mineralizers, firing cycles and quality of quartzite.

**Blast furnace ironmaking / 276**

## THE NEXT GENERATION COPPER STAVE

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Primarily used in the high heat zones of the furnace the copper stave has proved to be a hugely popular choice for blast furnace cooling. Despite its many successes, some plants have suffered with copper stave problems in two particular areas: stave bending (leading to water leaks at back of the stave) and stave wear (erosion on the hot face). The root causes of these failures can be defined by a number of factors including the furnace profile, the design and fixing of the stave, and the operation of the furnace. Primetals has had great success with copper staves, but understands the need to develop solutions for those plants with problems, and to provide a more robust solution to take copper staves to the next generation. This paper will describe the technology that Primetals' blast furnace technology team have developed.

**Environmental control in coke and ironmaking / 277**

## REDUCING THE COST OF BF TOP GAS DUST HANDLING, WITH PRACTICABLE PAYBACK

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The majority of existing blast furnaces plants use a dustcatcher as the primary process for removal of the process dust from the top gas. In recent years, there has been a trend to replace the dustcatcher with a cyclone: increasing the efficiency of dust removal, increasing the dry dust recycle to (for example) the sinter plant, and reducing the sludge volume generated from wet gas cleaning. This change provides a reduction in operation expenditure, but with the cost of installing a new cyclone with the necessary plant modifications – changes which can take considerable time and cost within the arrangement of an operating blast furnace. In order to reduce these problems of capital cost and shutdown time, Primetals have developed a solution to convert a dustcatcher into a cyclone, retaining the OPEX advantage at significantly reduced CAPEX. The paper will describe the technology that Primetals have developed.

**Modelling and simulation in coke and ironmaking / 278**

## PREDICTION OF BLAST FURNACE HEARTH CONDITION: THEORY AND PRACTICE

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In a modern blast furnace (BF) operation, the hearth is a critical area influencing both the routine casting performance and campaign life, where the liquid flow distribution, coke bed structure and condition, and the in-service refractory profile are all contributing factors. However, direct measurement is nearly impossible because of the high temperature conditions in the hearth. In practice, the refractory temperature distribution is a valuable measurement for assessing the hearth condition, e.g. the coke bed state and/or refractory erosion. However, for both normal furnace operations and long maintenance shutdown periods, the refractory temperature cannot fully provide a comprehensive and necessary assessment of this condition. In this regard, mathematical modelling, often coupled with physical modelling, has played an important role in interpreting the refractory temperature distribution in terms of liquid flow distribution, coke bed properties, hearth wear condition, and so forth. One aspect of the present investigation involved using a new, improved conjugate heat transfer model to describe the flow of liquid iron coupled with liquid-refractory heat transfer in the hearth of Port Kembla No. 5 Blast Furnace, under normal operating conditions. The model was carefully validated through a comparison between measured refractory data and model predictions. Results show that the actual range in measured pad temperature fluctuation over the course of the present campaign were well within the temperature difference expected for the float/sink movement of the coke bed. In the second aspect involved the development and application of a new transient numerical model developed to simulate hearth cooling during an extended maintenance shutdown period. In this model, the mushy zone was tracked so as to predict the temporal variation of refractory temperatures and critically, the extent of liquid bath cooling during extended shutdowns of several days duration. During the course of the shutdown, these results proved to be a very useful guide for furnace and maintenance engineers.

**Postersession and Coffee Break / 279**

## DESIGN AND COMMISSIONING OF AN EXPERIMENTAL FLUIDIZED BED REACTOR FOR THE HYDROGEN REDUCTION OF TITANOMAGNETITE IRONSAND

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Substantial deposits of titanomagnetite ironsand are found throughout the west coast of the North Island of New Zealand (NZ). This titaniferous iron ore contains approximately 8% TiO<sub>2</sub> equivalent, which prevents its use as a feedstock concentrate for conventional blast furnace (BF) processes. However, at present ~1.5 Mt pa is utilized in the rotary-kiln production of direct reduced iron (DRI), and a further > 1 Mt is exported for blending as a minority component within BF sinters. However, the increased focus on reduced CO<sub>2</sub> emissions is now promoting renewed interest in alternatives to existing carbo-thermic DRI approaches. Here, we report initial investigative work into the production of DRI from NZ ironsand via hydrogen-reduction in an experimental fluidized bed reactor.

NZ ironsand exhibits a naturally-occurring particle size distribution in the range 100-250  $\mu\text{m}$ , making it potentially well-suited to fluidized bed processing. Fluidized bed processing provides potential advantage for direct use of ironsand powder without pre-treatment of material such as pelletizing and sintering. In the current project, we have determined fluidization parameters for ironsand powder through theoretical calculation and experimental validation. We have then designed and commissioned a small-scale experimental reactor that enables fluidized bed reduction in Ar-H<sub>2</sub> atmospheres at up to 1050 °C. This experimental reactor includes a novel in-situ sampling system which utilizes a micro-cyclone to extract small amount of samples (< 5 g) of partially reduced material at specific time intervals during a batch reduction. We present initial results from this reactor, and compare metallization degree measurements of partially reduced ironsand powder using both quantitative X-ray diffraction (q-XRD) and titration techniques respectively. We show that q-XRD is a useful high-throughput approach to characterize reduction kinetics in this experiment. Finally, we discuss the onset of ‘sticking’ phenomena within this fluidized bed system, and the limitations this imposes on high-temperature rapid reduction of NZ ironsand in a fluidized bed reactor.

**Cokemaking / 280**

## **AN ASSESSMENT OF THE EFFECTS OF CALCIA AND CALCIUM ALUMINATE ON THE REACTIVITY OF THE COKE ANALOGUE**

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Coke is a key reagent in the iron blast furnace process. To enhance its performance in the blast furnace a better understanding of the kinetics of coke reactions in the blast furnace is necessary. Using a synthetic coke (coke analogue) the gasification rate in CO<sub>2</sub> of a coke containing calcia and calcium aluminates (CA6, CA, C3A) was studied. The coke analogue is a laboratory material with simplified carbon structure that has a mineral component with a particle size, size distribution and mineral dispersion that can be controlled. The analogues were reacted isothermally with CO<sub>2</sub> in the temperature range of 1173 – 1623 K. It was found that the reaction rate increased with increasing CaO activity/number of moles of Ca in the mineral. The relative reaction rates (from lowest to highest) of the analogues doped were alumina, CA6, CA, C3A and lime. The relative apparent activation energies of the gasification from lowest to highest was lime, C3A, CA, CA6 and alumina.

**Recycling of in-plant residues / 281**

## **CHARACTERISATION OF SELF-SINTERING BOS DUST**

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The recycling of steel plant by-products is a key issue for all steelmakers. For these materials to be fully utilised without incurring environmental and economical penalties they need to be

better understood with respect to their composition (morphology, phases and phase distribution). Research is being undertaken that aims to realise the value of steel plant by-products to the Australian steel industry and minimise the amount of by-product going to long-term stockpile. Basic oxygen steelmaking (BOS) dust, is a major steel plant by-product stream that has been characterised. This characterisation will inform the assessment of reactivity of the material so that its potential use on plant or elsewhere can be evaluated. While BOS dust contains useful components such as iron units and fluxes, other components, such as zinc, can limit the amount of possible recycling within the steel manufacturing process, causing both process and/or occupational health and safety issues.

BOS dust has been found to undergo a self-sintering process, improving its mechanical properties to allow easier recycling and utilisation on plant. It contains components including iron, flux and zinc units which have value on plant and elsewhere. Better understanding of the self-sintering process will allow better utilisation of this resource and help to minimise emissions and reduce costs by replacement of raw materials. In this paper, BOS dust characterisation by scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS), X-ray diffraction (XRD), thermo-gravimetric analysis (TGA) and differential calorimetry (DSC) is presented and discussed.

### Direct reduction / 282

## REDUCTION OF TITANOHEMATITE PELLETS BY HYDROGEN GAS

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Ironsand is a potential cheap source of iron with possible other values such as titania and vanadium oxide. Direct reduction is regarded as one of the promising processes to deal with ironsand in both an economically and environmentally sustainable manner. In this study, the reduction characteristics of pelletised ironsand ore by hydrogen gas were investigated. The pelletising and sintering of the ore is an oxidation process and results in the ironsand transforming to titanohematite (TTH).

A thermogravimetric technique has been used to evaluate the kinetics and X-ray diffraction used to establish the phase distribution before and after the reduction experiments. The experiments were carried out isothermally between 800-1200°C under pure hydrogen. As expected the reduction rate increased with temperature and metallic iron and ilmenite were found in the reduced pellets at all temperatures. At 900°C and below Ti was also present as rutile, while at temperatures >900°C the second Ti bearing phase was pseudobrookite.

Attempts to use a simple single interface shrinking core model (SCM) to represent the kinetics proved problematic and did not represent the experimental results well. It is likely that this is a result of the reduction process being more complex than this single interface model. Future work is focused developing a more rigorous approach to the kinetics and establishing the reaction interfaces and composition gradients within the pellet.

### Pelletising / 283

## PHASE DEVELOPMENT OF TITANOMAGNETITE IRON-SAND DURING OXIDIZING CONDITIONS.

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New Zealand ironsand is an unconventional titaniferous ore (typically ~8% TiO<sub>2</sub> by mass) which is commercially utilised to produce DRI, and as a blending component within BF sinters. Oxidative sintering of this titanomagnetite sand enables high-strength porous pellets to be formed, and such pre-oxidation is known to significantly enhance the gas-solid reduction rate compared to unoxidised ironsand. This is attributed to the increase in available surface area which results from cracking of individual grains during oxidation. However, the fate of titanium during oxidation has not been extensively studied, despite titanium playing an important role in the overall kinetics and yield of subsequent direct-reduction processes.

In this work we report a detailed study of the evolution of titanium-bearing phases during the controlled oxidation of NZ ironsand pellets. Samples were oxidised in air at temperatures between 800 °C and 1300 °C, and then characterised using FEG-SEM, EDS, EBSD and XRD. Electron microscopy shows localised regions of titanium enrichment within the oxidised grains, and we observe the emergence of pseudo-brookite and ilmenite phases during the oxidation process. Our results indicate that titanium is highly mobile within individual oxidised grains, and that the final phase composition is strongly affected by both oxidising temperature and time.

**Blast furnace ironmaking / 284**

## PHYSICO-CHEMICAL BEHAVIOUR OF OLIVINE IRON ORE PELLETS MIXED WITH NUT COKE UNDER SIMULATED BLAST FURNACE CONDITIONS

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Blast furnace productivity is limited by the resistance offered to the gas flow in the cohesive zone. Mixed use of nut coke with iron ore proved beneficial for decreasing this resistance. In present study effect of nut coke addition on the olivine iron ore pellet bed was studied under simulated blast furnace condition. Nut coke mixing degree (replacement of regular coke) varied from 0 to 40 wt% to study the physicochemical changes that it brings on pellet bed. The difference between the softening and melting temperature decreases with the nut coke addition. The softening temperature increases due to increase in reduction degree of the pellets. The melting temperature decreases due to the higher carbonisation degree of iron shell. During melting, the magnitude of the pressure drop peak decreases with the increase in nut coke concentration

**Direct reduction / 285**

## FURTHER OPPORTUNITIES OF COMPETITIVENESS IMPROVEMENTS FOR DIRECT REDUCTION PLANTS

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Midrex and Primetals Technologies have successfully completed their latest HBI projects for voestalpine Texas LLC/USA and LGOK/Russia. This paper discusses some further possibilities for improvements of Direct reduction plants in order to increase the plant competitiveness and/or flexibility. Such plant improvements have been either already implemented in the latest projects for the first time or were recently developed by Midrex and/or Primetals Technologies. Some of this plant improvements are:

- Waste Heat Recovery for Top gas and Reformer Flue Gas – Production of steam or electricity based on framework conditions
- Bottom Seal Gas Hot Dry Dedusting System – Recovery of hot DRI dust for increase of product yield
- Slurry Treatment by Chamber Filter Presses – Efficient dewatering of slurry from clarifier with low operating and maintenance cost
- Process Water Degasser – Degassing of process water from CO<sub>2</sub> to improve water quality and operation/maintenance cost
- Adjustable Carbon Technology (ACT) – Increase of carbon content depending on HBI off-taker/user requirements
- DRIPAX Carbon and Metallization Prediction – Improvement of plant operation by stable operation
- Level-2 Expert System Improvements – Increased support of operation team

Such improvements either reduce the OPEX costs, increase the yield, improve the operation/maintenance and/or increase the availability of a Midrex plant and can be implemented for new direct reduction plants or retrofitted for existing plants.

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## **THE HIGH FLUIDITY OF BARRO BRANCO COAL (BRAZIL) AND ITS INFLUENCE ON COKE QUALITY**

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Brazil has a large coal reserve, which is mainly located in the Parana Basin, southern region of the country. Despite that, the steel sector, which is the largest coal consumer in Brazil, needs to import 100% of its demand. The coal from Barro Branco seam in Santa Catarina-Brazil is a potential raw material for coke production due to its well-known coking properties. Thus, the present study aimed to evaluate and justify the thermoplastic behavior of Barro Branco coal, as well as to investigate its influence on the metallurgical coke quality. The results indicated that the Barro Branco coal presents extremely developed thermoplastic properties when compared to imported coking coals. This characteristic seems to be associated with possible impregnation of bitumen in petrographic components of the vitrinite group. Barro Branco coal promoted an important increase of the thermoplastic properties of coal blends. In general, it was observed that Barro Branco coal caused a decrease on coke quality. However, the use of this coal is favored in coal blends containing high inert content.

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## **COKE MICROSTRUCTURE - SAMPLE PREPARATION AND IMAGE ANALYSIS VIA IMAGEJ**



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Metallurgical coke remains an irreplaceable material in the production of hot metal in blast furnaces, providing the heat and the reducible gases necessary for the process. Coke also play an important structural role in the blast furnace, providing a permeable bed for the passage of gases and liquids. Coke mechanical strength is a key factor for the performance of blast furnace and is essentially governed by coke microstructure. The microstructure of metallurgical coke can be defined as the spatial distribution of the coke carbonaceous matrix and its porosity. In this work, a methodology was developed to perform a representative characterization of coke microstructure. Cokes were produced from individual coals and coal blends in laboratory and pilot scale. Particles of these cokes were prepared and observed under an optical microscope to obtain images that were later analyzed in open source software (ImageJ) using a sequence of commands to obtain the microstructure parameters, such as porosity, average pore size, pore size distribution, wall thickness and pore shape. The influence of variables such as coke particle size, number of coke particles and number of images per sample on coke microstructure parameters was investigated. In addition, this work will present the step by step commands performed in the image analysis software to obtain the coke microstructure parameters. The geometric parameters, together with a porosity, form the set of data that can be correlated with mechanical strength of coke.

**Blast furnace ironmaking / 292**

## NEW COOLING TECHNOLOGY FOR REDEFINING STAVE LIFE

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Copper stave failure is a major cause for interim blast furnace repairs, at great cost to the blast furnace owner, primarily due to: a) abrasive wear on the exposed hot-face; b) cracking of welded pipe connections; and c) low cooling density resulting from ineffective cooling layout. Under these damaging conditions, traditional staves often begin to leak water, overheat and exhibit cascading wear around the furnace. Hatch has developed a new and novel stave design to address premature failures that have plagued the industry. These staves feature a metallurgically-bonded abrasion-resistant composite hot-face, providing superior abrasion resistance compared to traditional copper staves, as verified by third-party testing. The metallurgical bond allows for a high level of heat extraction through the hardened layer, maintaining a cold surface conducive to the formation of protective accretions not achievable by traditional mechanically-fixed refractory bricks. Advanced blast furnace cooling technologies and applications for managing premature stave wear will be presented, including specific discussion around imminent stave failure diagnosis, new blast furnace cooling technology (i.e. abrasion-resistant staves) and applications implemented on operating blast furnaces.

**Direct reduction / 293**

## SUSTAINABLE DECREASE OF CO<sub>2</sub> EMISSIONS IN THE STEELMAKING INDUSTRY BY MEANS OF THE EN-ERGIRON DIRECT REDUCTION TECHNOLOGY

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Compared to the traditional Blast Furnace – Basic Oxygen Furnace way of producing steel, more than 50% of CO<sub>2</sub> emissions can be saved if steel is produced by means of the Energiron Direct Reduction – Electric Arc Furnace way. This target is achieved partly thanks to the use of reducing sources cleaner than coal, and partly thanks to the selective capture of up to 90% of the CO<sub>2</sub> produced, that can be possibly commercialized as a valuable by-product for several different industries. The investment cost of a DR-EAF minimills is lower than the BF-BOF configuration, therefore in principle this is a sustainable solution to decrease CO<sub>2</sub> emissions in the steel industry. Operating costs are competitive provided that the reducing agent is available at reasonable price: the Energiron process can use either natural gas, syngas and BF off-gas, whichever is locally available at the cheapest price. Further than this, even Hydrogen can be used as reducing gas, without any modification to the original Energiron process scheme. This allows further reductions in CO<sub>2</sub> emissions, as many technologies are being developed to exploit renewable energy sources for production of Hydrogen, which is generally considered to be the fundamental element for the future global energy system.

**Modelling and simulation in coke and ironmaking / 294**

## **SOFTENING AND MELTING MODELING OF IRON ORE PARTICLES USING A DISCRETE-CONTINUOUS COUPLING METHOD**

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The blast furnace iron making is the main method to produce liquid iron. A blast furnace is charged with ore and coke from the top along with a preheated gas introduced to the furnace through the tuyeres in the lower part. The combustion of coke generates reducing gas ascending through the blast furnace to reduce iron-bearing materials. The reduced iron-bearing particles start softening and melting because of the weight of burden above and the high temperature in the middle of the blast furnace so-called cohesive zone. In this region, as particles are softened, the void space between particles decreases. As the temperature increases further, the softened particles start melting and generate two different liquids: molten iron and slag. Then the generated liquids trickle down to the lower part of the blast furnace. The softening and melting process forms the impermeable ferrous layers forcing gas to flow horizontally through the permeable coke windows. This causes a high-pressure drop. Softening and melting has a big effect on the operation of the blast furnace and since it is not possible to interrupt the blast furnace to investigate details of the phenomena occurring inside, the numerical simulation becomes more practical. In this contribution, the eXtended Discrete Element Method (XDEM) [1,2] as an advanced numerical tool based on the Eulerian-Lagrangian framework, is used. Within this platform, the gas and liquid phases are described by computational fluid dynamics (CFD) and the soft-sphere discrete element approach (DEM) is used for the coke and iron ore particles. Continuous phases are coupled to the discrete entities through mass, momentum, and energy exchange. Moreover, the internal temperature distribution of the particles is described. Therefore, the XDEM is able to model multiphase and multiscale phenomena as can occur in the cohesive zone. The particle's deformation, temperature, melting, and shrinking along with gas and liquids pressure, temperature and velocity patterns are examined using the XDEM method.

**Sintering / 295**

## **FIVE DECADES OF SINTER MAKING AT TATA STEEL – A CONTINUOUS IMPROVEMENT JOURNEY**

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Tata Steel is the pioneer in steel industry of India. Production started way back in 1911. However, the first sinter plant (known as SP1) was commissioned in 1958. It was a modest beginning at first, with production of acid sinter. Tata Steel has been sintering captive iron ore fines having high alumina (above 4%) and silica (about 1%). This typically represents the Indian situation where most iron ore are characterized by high alumina to silica ratio. This contrasts with the internationally available ore fines having alumina around 1.0%. High alumina in iron ore fines pose difficulty during sintering such as requirement of high heat input, lower productivity and poor sinter quality (e.g. high RDI, low RI, low Tumbler Index, and so on). The story of sinter making at Tata Steel over last 5 decades is indeed a technical account of converting the odds into advantage. The paper will describe significant discoveries made through lab trials which were adopted in regular operation. A rich learning experience of achieving productivity as high as 42 t/m<sup>2</sup>/d, starting from around 20 t/m<sup>2</sup>/d. It will be of greater importance to know the impact of having wide variation in sinter chemistry regimes, as shown below and its impact on sinter properties.

**Smelting reduction / 296**

## 1ST CAMPAIGN HISTORY AND REVAMPING RESULTS OF #2 FINEX

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The FINEX® process has been developed since 1992, starting from lab scale tests to constructing a pilot, a demo and two industrial plants consecutively in Pohang Works, South Korea. It has been 11 years since the first 1.5 MTPA commercial plant, #2 FINEX, began operating. The cumulative production of #2 FINEX achieved 14 million tons of hot metal and the availability in 2017 hit the record high with 96.6%. During this period, significant improvements were carried out by verifying the long-term cokeless operations, adapting a heat recovery system, increasing the process efficiency of the hot compacted iron system, changing binders for coal briquettes and etc. A minor revamping was performed during the 1st half of 2018 to apply advanced structures in the fluidized bed reactors and the reduction shaft. The inspection results during the revamping period of #2 FINEX will be great source for the next operation and design.

**Blast furnace ironmaking / 297**

## BLAST FURNACE PROCESS OPTIMIZATION SYSTEM – TOOL FOR RISK & KNOWLEDGE MANAGEMENT

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The steps from data to information to knowledge and finally standardized operation for the blast furnace are put into the overall picture of digitalization in the ironmaking area. By introduction of expert systems individual judgement of process conditions and required actions receive support by rule based decision systems with an incorporated, standardized operation strategy that has been jointly elaborated for the individual furnace. As the expert system contains the key operational strategy it mirrors central operational know how that can be adjusted and extended based on the gain of further insight, meeting the specific risk mitigation requirements and operational targets.

By model supported analysis of the operational condition an early detection of undesired deviations allow to go closer to the operational limits – but still run the furnace in the safe range. By this, improved results regarding BF performance, fuel rates and operational stability can be achieved. The paper shows practical examples of critical operational conditions of the blast furnace and the corrective actions automatically suggested and executed by the expert system. Finally, we outline the possibilities of project specific extensions of the expert system to adjust it to specific operational requirements.

**Direct reduction / 298**

## LABORATORY STUDY OF REDUCTION KINETICS IN A DRI SHAFT FURNACE

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This article presents a novel experimental procedure that simulates the complicated counter-current DR shaft process. This lab test is recently developed in ArcelorMittal Global R&D and shows good correlation with actual direct reduction process. The method provides a unique tool to study the impact of DR plant operation parameters in the laboratory scale, and enables the study of raw materials evolution from Oxide pellet to DRI.

**Blast furnace ironmaking / 299**

## USE OF HBI IN BLAST FURNACE

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Direct reduced iron (DRI) can be used after briquetting in form of HBI in the blast furnace to decrease the consumption of reducing agents as well as to increase the production of hot metal. voestalpine Stahl GmbH Linz uses HBI from its own plant in Corpus Christi (Texas) at the blast furnaces 5 and 6. In this article the influence of the usage of HBI in the blast furnaces on the consumption of reducing agents, productivity, blast furnace operation and hot metal quality is discussed.

**Cokemaking / 300**

## COKE PORE STRUCTURE ANALYSIS USING X-RAY CT

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Development of coke production technology which can maintain high coke strength with use of certain amount of low rank coal is needed. Accordingly, it is important to investigate influence of coke pore structure on coke strength and dominant factors of coke strength. Anraku et al. established a Stress simulation method by using three-dimension images of coke which were taken by X-ray CT. In this presentation, results of three-dimensional numerical analysis such as components of coke structure and Mises stress of two types of high strength coke will be presented.

**Blast furnace ironmaking / 301****EXPERIENCE OF IMPLEMENTING INNOVATIVE COOLING SYSTEMS IN BLAST FURNACE PRODUCTION****Author(s):** VYNOHRADOV, Olexandr<sup>1</sup>**Co-author(s):** KALANTARENKO, Andrii<sup>2</sup>; TSYHULOV, Yurii<sup>1</sup>; KROTYUK, Anton<sup>3</sup><sup>1</sup> *M Technology LLC*<sup>2</sup> *TeraWatt Group LLC,*<sup>3</sup> *TeraWatt Solutions GmbH***Corresponding Author(s):** melanie.baumgartner@asmet.at

Throughout the past 3 years TeraWatt Group have participated in over than 30 blast furnace reconstruction projects. Over a dozen projects were focused on solving one of the most challenging issues of the modern blast furnace process – significant standard cooling system (with untreated water) useful lifetime decrease, caused by rapid failure of cooling plates under pulverized coal injection conditions. Today cooling system efficiency impacts blast furnace lifetime. Therefore, modern cooling systems require higher reliability and uptime operational parameters. M Technology cooling system design provides the following features which are significantly more important under pulverized coal injection conditions: – effective heat removal from cooling plates and lining; – formation and maintenance of a stable skull layer on the lining surface; – energy efficiency, cooling system heat loss reduction, coke saving; – environmental impact reduction by using closed-loop (water recycling) cooling systems or lower load on the enterprise's recirculation; – BF lifetime extension up to 15 years. We have implemented a lot of innovative approaches, modern math and 3D modeling software while working on our projects and technology. We are proud that our customer, the largest steel making holding in Ukraine and one of leaders worldwide – METINVEST HOLDING has approved patented by M Technology blast furnace cooling system solution as standard for all new blast furnace constructions, revampings. The article describes the innovations and devolvement of modern cooling systems on the example of the following implemented and well-proven facilities (including cooling staves, pump station, automation system design, math modeling principles): – Zaporizhstal PJSC BF-2, BF-3, BF-4, BF-5. – Azovstal Iron & Steel Works PJSC BF-3, BF-4, and BF-6. – Ilyich Iron & Steel Works PJSC BF-4.

**Automation and digitalization in coke and ironmaking / 302****SENSORS AND IOT STRATEGIES IN THE MODERN STEEL INDUSTRY**NUJIC, IVICA<sup>1</sup><sup>1</sup> *WIKA Alexander Wiegand SE & Co. KG***Corresponding Author(s):** melanie.baumgartner@asmet.at

Efficiency, Productivity, Reliability in conjunction with Big Data analysis are key requirements to secure a competitive position in the steel industry. It all starts with the collection of data provided by sensing elements in the measurement points. Durability, repeatability and long-term stability beats oversophisticated and overpriced measurement solutions. Reliable and interconnected-sensing / value collection is the direct way to efficiency and productivity sweet spots. Human Machine Interfacing and IoT connectivity with preventive status flags are the correcting and improving efficiency-drivers.