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Potential of Air Classification for Zinc Management in Dust Recycling in Ironmaking

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The dusts generated in the blast furnace process are partly recycled via the sinter plant. The amount of Zn which is recycled with these dusts is limited to avoid operational problems. Usually, the dusts from the dust catcher and the cast house dust are recycled, while the residue from second stage top-gas de-dusting has to be discharged at least partly. In this study the application of air classification was investigated for maximization of the recycled fractions of the dusts at certain limits for the amount of recycled Zn. For this, approximation functions for the dependence of the Zn content in the coarse material on the fraction of the coarse material had to be derived from classification experiments. The calculations showed that the positive effect of air classification was higher at lower values of the limit for the amount of Zn recycled with the dust. Depending on the value of this limit the possible increase in dust recycling in comparison to classification of the second stage filter dust only ranged from 0.27 to 0.45 kg/t HM for air classification of second stage filter dust and cast house dust and from 0.35 to 0.79 kg/t HM for classification of all three dusts.

KEY WORDS: blast furnace; dust recycling; zinc; air classification.

1. Introduction

In integrated steel mills the ironmaking process usually involves two main process units, the sinter plant and the blast furnace (BF). The BF provides the hot metal (HM) or pig iron by reducing the iron ore into metallic iron. In the sinter plant fine iron ores are agglomerated together with fluxes and iron-rich in-plant return fines as charge material for the BF. **Figure 1** shows the schematic flow diagram of the ironmaking process.

The off-gas (top-gas) discharged from the BF is de-dusted in two stages before it can be used as fuel. In the first de-dusting stage the coarse dust is separated by a dust-catcher or a cyclone. The second de-dusting stage usually comprises of a venturi scrubber or an annular gap scrubber. In recent years an increasing number of dry second-stage de-dusting systems have been installed at BFs.[1,2] A considerable amount of residues results from BF top-gas de-dusting: 3.4–18 kg dust per ton of HM from the first de-dusting stage and 2.0–22.3 kg sludge per ton HM from the second de-dusting stage have been reported for European BFs.[3] The reported Zn content is 0.1–0.5% Zn and 1.0–10% Zn for the first stage and second stage residue respectively. Most of the dust from first stage de-dusting is recycled to the sinter feed,[3–5] while the sludge from second-stage wet de-dusting is mainly discharged to landfill sites because of the higher Zn content.[6] Zn is an unwanted component in the feed material to the sinter plant because it causes problems in the BF operation. Zn forms crusts in the upper part of the BF and accumulates in the furnace lining which consequently deteriorates.[7–9] For this reason the total amount of Zn in the charge of a BF is usually restricted to 100–150 g/t of HM produced.[3] The main source of Zn in the charge of a BF is usually the sinter.[7] A significant fraction of the Zn in the sinter originates from recycled materials, especially dusts from the de-dusting of the BF, but also the ores, the coke and the fluxes contain some Zn.[10] In the sintering process some Zn is removed by volatilization and discharged with the off-gas. However, the Zn reduction in the sintering process is quite small.[11] The off-gas from the sinter plant is usually de-dusted by an electrostatic precipitator (ESP). The ESP dust is usually recycled in the sinter plant. In this case all Zn contained in the feed material of the sinter plant is finally contained in the sinter produced. In some sinter plants the dust collected in the last electrical field of the ESP is excluded from recycling because of the increased chloride content of this dust.[3,12] However, the Zn content of this dust is not increased[13] and therefore, the possible removal of Zn via this path is quite small. Thus, the Zn content in the feed material of the sinter plant has to be limited according to plant specific conditions.

To enable partial recycling of the sludge from wet second-stage BF de-dusting a separation process is established that applies hydrocyclones.[3,14–16] In this process the sludge is separated into a coarse fraction for recycling to the sinter

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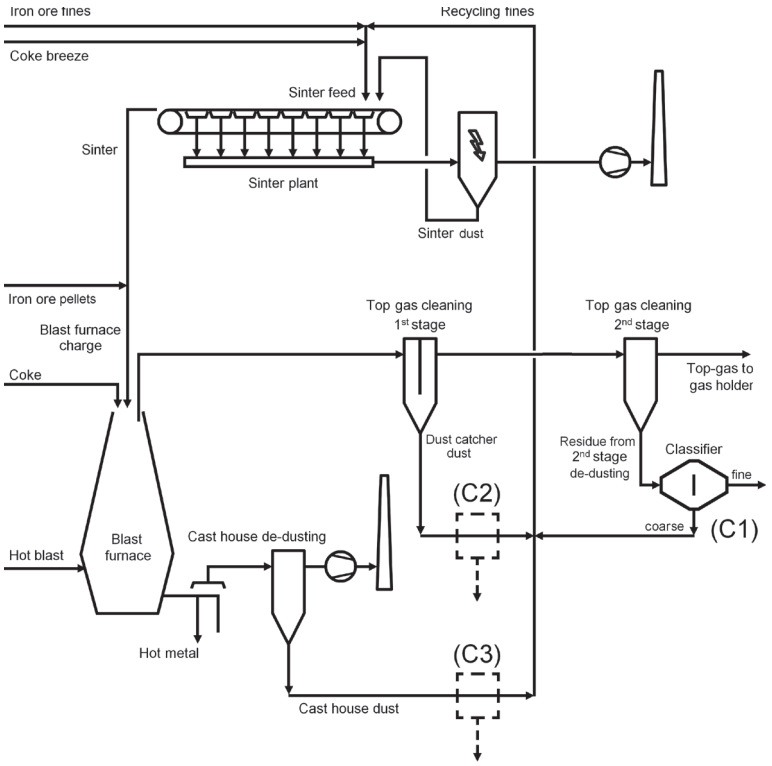

Fig. 1. Schematic flow diagram of the ironmaking process; (C1): classification of second-stage top-gas de-dusting dust; (C2): possible classification of dust catcher dust; (C3): possible classification of cast house dust).

plant which is depleted in Zn and a fine fraction which is enriched in Zn (Fig. 1, (C1)). This separation is possible because Zn is enriched in the fine fractions of the residue. For the recycling of the dust collected in dry second-stage BF de-dusting, air classification of the dust can be applied in a similar way.[17,18] Air classification can also be used for the treatment of the BF dust collected in the first de-dusting stage (Fig. 1, (C2)). The enrichment of Zn in the fine dust fraction enables a separation of a Zn-rich fine fraction leaving the coarser bulk of the dust with a reduced Zn concentration.[19]

Dusts with a higher Zn content, *e.g.* the fine Zn-enriched fraction produced in a classification process, can be recycled in the basic oxygen furnace (BOF)[3,20–22] or discharged to external treatment for Zn recovery in the Zn industry.[8,23,24]

Another source of dust emissions in the BF process is the periodically casting of the iron and the slag which is performed in the cast house. Once a tap-hole is drilled through the refractory clay plug, liquid iron and slag flow down into the runners. Most of the dust emissions originate from the tapping, but also at the point where the iron is tipped into a transfer ladle, a considerable amount of dust is generated. The dust emission problem in the cast house is tackled by extraction of the fumes via exhaust hoods. The dust is separated from the extracted air by a fabric filter or an electrostatic precipitator.[25–27] An average amount of cast house dust produced per ton of HM of 0.6–5.1 kg has been reported for European blast furnaces.[3] Only little information about cast house dust is available in the literature. The typical particle size distribution and other physical properties have been reported recently.[28] The cast house dust consists mainly of fine granular iron oxide[29] but also contains some Zn.[10,30] Approximately 86% of the cast house dust is recycled to the sinter plant to recycle the iron and avoid landfill.[31–33] In some BFs this dust is recycled back to the BF after cold briquetting or by direct injection at the tuyère level.[3]

The aim of this study was to investigate the use of air classification for increased recycling of the residues from off-gas de-dusting within the ironmaking operation. While for both dusts from the de-dusting of the BF top-gas some results for the efficiency of air classification for Zn separation are available, no data is available for the dust from cast house de-dusting. Thus, firstly the distribution of Zn in the size fractions of cast house dust was investigated (Fig. 1, (C3)). With this information, in addition to the results derived from literature data for the other dusts, the application of air classification for the treatment of reverts to the sinter plant was evaluated. The focus was the maximization of the amount of dust recycled to the sinter plant under certain limits for the amount of Zn contained in this recycled dust.

2. Material and Methods

2.1. Dust Samples

The dusts investigated (D1, D2) originated from the cast house de-dusting systems of two industrial blast furnaces. In both systems a fabric filter is used for de-dusting. The dust sample with the higher Zn content (D2) was split into five size fractions using a laboratory air classifier (100 MZR from Hosokawa Alpine). The speed of the classifier wheel in the four classification runs was 21 000 rpm, 11 000 rpm, 6 000 rpm and 3 000 rpm. A schematic diagram of the classification procedure is shown in **Fig. 2**. A detailed description of such a sequential classification procedure can

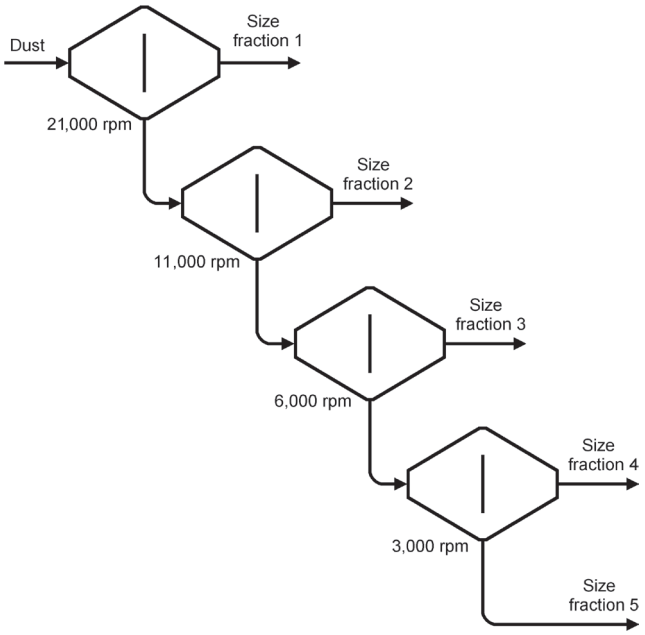

Fig. 2. Schematic diagram of the classification procedure.

be found elsewhere.[18)]

2.2. Measurements

For the measurement of the particle size distribution and for chemical analysis the volumes of the dust samples were reduced to the volume suitable for the measurements using sample dividers (Haver & Boecker HAVER RT and Quantachrome Micro Riffler).

The moisture content of the dust samples was measured gravimetrically using a infrared moisture analyser (MA35M from Sartorius). The particle size distribution of the dust samples was measured using a laser diffraction instrument (HELOS/RODOS from Sympatec) with dry sample dispersion. For the verification of the calibration of the instrument, a SiC-P600'06 standard from Sympatec was used. The target value for the mass median diameter of the standard is 25.59 μm and the measured value for the mass median diameter was 25.62 μm.

Prior to analysis the solid samples were dissolved by aqua regia digestion. The concentration of Zn was measured by inductively-coupled plasma optical emission spectroscopy (Horiba Jobin Yvon Ultima 2 system) testing each dust sample in duplicate. The average values are presented in the results. The details of the analytical methods can be found elsewhere.[34)]

2.3. Calculation

Practically all Zn fed to the BF leaves it with the dusts. The amount of Zn contained in the pig iron and the slag is comparatively small.[10)] Therefore, only part of the dust can be recycled to the sinter plant because also the ore, the coke and the fluxes contain some Zn. In the sinter plant nearly all Zn contained in the feed is discharged with the sinter because the dust collected from the sinter plant off-gas is recycled to the feed. Thus, the amount of Zn recycled with the dust m_{Zn} has to be less than the Zn limit of 100–150 g/t of HM. A typical value for m_{Zn} is in the range of 40–80 g/t of hot metal.[10)]

For the calculation, all mass flows can be related to 1 ton of HM. The total mass of recycled dust m_r results from the mass of the various dust recycled i (Eq. (1)):

$$m_r = \sum_i m_{r,i} \quad \text{..... (1)}$$

while the total amount of Zn m_{Zn} recycled with the dust results from the mass of the Zn in the various recycled dusts (Eq. (2)):

$$m_{Zn} = \sum_i m_{Zn,i} \quad \text{..... (2)}$$

The recycled amount of a certain dust is given by the amount of dust produced in the respective de-dusting system m_i and the fraction of the dust which is recycled $x_{r,i}$ (Eq. (3)):

$$m_{r,i} = m_i \cdot x_{r,i} \quad \text{..... (3)}$$

For the amount of Zn contained in a recycled dust, the mass fraction of Zn $x_{Zn,i}$ in the recycled dust has to be considered (Eq. (4)):

$$m_{Zn,i} = m_i \cdot x_{r,i} \cdot x_{Zn,i} \quad \text{..... (4)}$$

When a dust is recycled without any treatment the mass fraction of Zn in the dust is identical to that present in the separated dust $x_{Zn,0,i}$. If the dust is treated by classification the mass fraction of Zn is not constant but a function of the fraction of the dust which is recycled. For the BF dusts previously investigated the dependence of the Zn content on the fraction of the coarse material separated for recycling can be approximated by functions of the following type (Eq. (5)):

$$x_{Zn,i} = x_{Zn,0,i} \cdot A_i \cdot e^{B_i \cdot x_{r,i}^{C_i}} \quad \text{..... (5)}$$

For the second stage filter dust from top-gas de-dusting[18)] the values derived for the parameters A, B and C by minimization of the sum of square of errors are 0.648, 0.43 and 9.5, respectively. For the dust catcher dust[19)] the respective values are 0.442, 0.79 and 9.0.

For the maximization of the amount of recycled dust m_{rec} the target function equation (Eq. (6)) has to be used, where the indices 1, 2 and 3 are for dust catcher dust, filter dust and cast house de-dusting dust, respectively:

$$m_{rec} = m_1 \cdot x_{r,1} + m_2 \cdot x_{r,2} + m_3 \cdot x_{r,3} \quad \text{..... (6)}$$

The constraint results from the limit for the amount of Zn in the recycled material m_{Zn} (Eq. (7)):

$$\begin{aligned} g\left(x_{r,1}, x_{r,2}, x_{r,3}\right) = m_{Zn} &- m_1 \cdot x_{r,1} \cdot x_{Zn,0,1} \cdot A_1 \cdot e^{B_1 \cdot x_{r,1}^{C_1}} \\ &- m_2 \cdot x_{r,2} \cdot x_{Zn,0,2} \cdot A_2 \cdot e^{B_2 \cdot x_{r,2}^{C_2}} \quad \text{... (7)} \\ &- m_3 \cdot x_{r,3} \cdot x_{Zn,0,3} \cdot A_3 \cdot e^{B_3 \cdot x_{r,3}^{C_3}} = 0 \end{aligned}$$

The extreme value problem can be solved applying the Lagrange multiplier method (Eqs. (8)–(11)):

$$\frac{\partial L}{\partial x_{r,1}} = \frac{\partial m_r}{\partial x_{r,1}} + \lambda \cdot \frac{\partial g}{\partial x_{r,1}} = 0 \quad \text{..... (8)}$$

$$\frac{\partial L}{\partial x_{r,2}} = \frac{\partial m_r}{\partial x_{r,2}} + \lambda \cdot \frac{\partial g}{\partial x_{r,2}} = 0 \quad \text{..... (9)}$$

$$\frac{\partial L}{\partial x_{r,3}} = \frac{\partial m_r}{\partial x_{r,3}} + \lambda \cdot \frac{\partial g}{\partial x_{r,3}} = 0 \quad \text{..... (10)}$$

$$\frac{\partial L}{\partial \lambda} = g\left(x_{r,1}, x_{r,2}, x_{r,3}\right) = 0 \quad \text{..... (11)}$$

The set of resulting equations Eqs. (12), (13) and (11) can be solved only numerically. For this the software Wolfram Mathematica 10.2 was used.

$$x_{Zn,0,1} \cdot A_1 \cdot e^{B_1 \cdot x_{r,1}^{C_1}} \cdot \left[1 + B_1 \cdot C_1 \cdot x_1^{C_1}\right] = x_{Zn,0,2} \cdot A_2 \cdot e^{B_2 \cdot x_{r,2}^{C_2}} \cdot \left[1 + B_2 \cdot C_2 \cdot x_2^{C_2}\right] \quad \text{..... (12)}$$

$$x_{Zn,0,1} \cdot A_1 \cdot e^{B_1 \cdot x_{r,1}^{C_1}} \cdot \left[1 + B_1 \cdot C_1 \cdot x_1^{C_1}\right] = x_{Zn,0,3} \cdot A_3 \cdot e^{B_3 \cdot x_{r,3}^{C_3}} \cdot \left[1 + B_3 \cdot C_3 \cdot x_3^{C_3}\right] \quad \text{..... (13)}$$

3. Results and Discussion

3.1. Air Classification of Cast House Dust

The concentration of Zn in cast house dust D1 and D2 was 8.2 and 14.9 g/kg dry dust, respectively. Also the particles size distribution of both cast house dusts was similar and the respective mass median diameters were 6.1 μm and 6.0 μm. The dust with the higher Zn content (dust D2) was selected for the classification experiment. The mass median diameter of the size fractions varied from 1.05 μm for the finest fraction to 35 μm for the coarsest fraction. The mass fractions of the five size fractions produced and their Zn and Fe content are summarized in **Table 1**.

The iron content does not vary very much with the particle size. The maximum concentration was found in the medium size fraction. In contrast, the highest concentration for Zn was found in the finest size fraction. With increasing particle size the concentration of Zn decreased from size fraction to size fraction.

The Zn content calculated for the two size fractions produced in a single classification run by a classification process with similar separation characteristics as the air classifier used in the experiment is shown in **Fig. 3**. The Zn content of the coarse material and the fine material is depicted as a function of the mass fraction of coarse material. The calculations required to obtain this diagram from the classification experiments are described elsewhere.[35] When only the finest material is separated by classification, the mass fraction of the remaining amount of coarse material for recycling is reduced slightly. The reduction of the Zn content in the coarse material is considerable and the Zn content in the fine fraction is high. With decreasing coarse mass fraction the Zn content of both size fractions decreases continuously.

The values for the parameters A, B and C in the approximation equation (Eq. (5)) for the Zn content in the coarse fraction of the cast house dust as a function of the mass fraction of the coarse material obtained by minimization of the sum of square of errors were 0.168, 1.75 and 1.33, respectively. These values are quite different in comparison to the parameters derived for the dusts from BF top-gas de-dusting. **Figure 4** shows the Zn content of the coarse material as a function of the mass fraction of coarse material for air classified dust catcher dust and 2nd stage filter dust based on published data.[18,19]

Table 1. Size fractions produced from the cast house dust D2.

	Mass fraction in %	Mass median diameter in μm	Fe content in g/kg	Zn content in g/kg
Size fraction 1	8.8	1.05	326	56.7
Size fraction 2	14.5	2.0	374	23.4
Size fraction 3	20.7	4.9	431	16.0
Size fraction 4	33.4	12.3	408	8.2
Size fraction 5	22.6	35	382	3.2

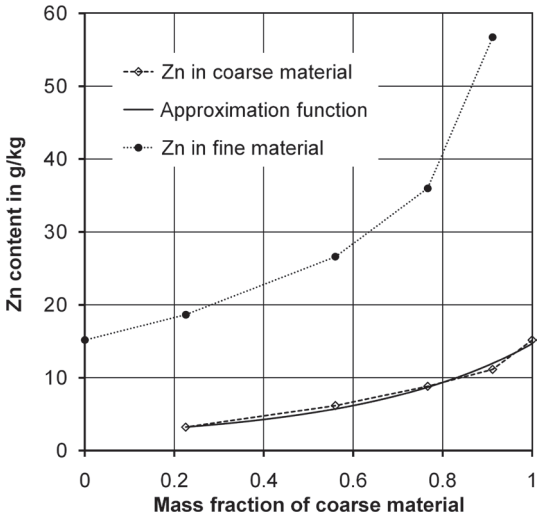

Fig. 3. Zn content in the coarse material and in the fine material as a function of the mass fraction of the coarse material.

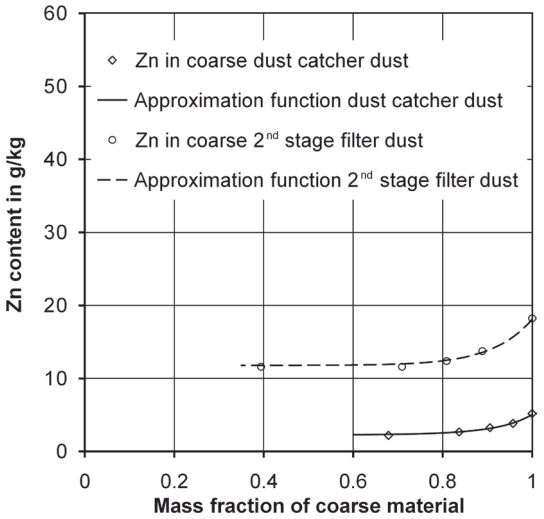

Fig. 4. Zn content in the coarse material as a function of the mass fraction of the coarse material for air classified dust catcher dust and 2nd stage filter dust.

3.2. Maximizing Dust Recycling in Ironmaking

For typical amounts of the residues from BF de-dusting (dust catcher dust: 7.0 kg/t HM; dry second-stage filter dust: 7.0 kg/tHM; cast house dust: 0.70 kg/t HM) with Zn

contents according to the reported ranges[3,10] various options for the use of air classification of the dusts prior to recycling to the sinter plant were compared. The chosen Zn content of the residues was 3.0 g/kg, 15.0 g/kg and 15.0 g/kg for the dust catcher dust, the filter dust and the cast house dust, respectively. The investigated options were:

1) Standard (O1): recycling of all dust catcher dust and cast house dust; classification of the second-stage filter dust and recycling of the coarse fraction;

2) Classification 2 (O2): recycling of all dust catcher dust; separate classification of the cast house dust and the second-stage filter dust and recycling of the coarse fractions;

3) Classification 3 (O3): separate classification of all three residues and recycling of the three coarse fractions.

The options were selected in the way that only dust with a low Zn content or with a small total amount is recycled without classification.

The option "Standard" corresponds to BFs with wet second-stage top-gas de-dusting systems which apply classification of the BF sludge with hydrocyclones.

The calculated fractions of dust which can be recycled to the sinter plant are summarized in **Table 2** for various values of the limit for the amount of Zn recycled. **Figure 5** shows the amount of dust which has to be excluded from recycling to the sinter plant. Naturally, when the limit for Zn is higher, the total amounts are lower. At a given Zn limit the highest amount of dust to be discharged results for the standard option O1 while the lowest amount can be achieved when all three dusts are classified (O3). The possible increase of dust recycling for the limits 40 and 60 g/t HM for option O2 and O3 compared to option O1 was nearly the same: approximately 0.45 kg/t HM for option O2 and approximately 0.77 kg/t HM for option O3. At the higher Zn limit of 80 g/t HM the possible increase of dust recycling was less; 0.27 g/t HM for option O2 and 0.35 g/t HM for option O3.

Table 2. Fractions of dust recycled (x_r).

	$x_{r,I}$ Standard	$x_{r,I}$ Classification 2	$x_{r,I}$ Classification 3
Zn limit for the dusts recycled to the sinter plant: 40 g/t HM			
Dust catcher dust	1	1	0.933
2nd stage filter dust	0.138	0.253	0.367
Cast house dust	1	0.503	0.503
Zn limit for the dusts recycled to the sinter plant: 60 g/t HM			
Dust catcher dust	1	1	0.939
2nd stage filter dust	0.432	0.546	0.648
Cast house dust	1	0.508	0.526
Zn limit for the dusts recycled to the sinter plant: 80 g/t HM			
Dust catcher dust	1	1	0.976
2nd stage filter dust	0.714	0.789	0.820
Cast house dust	1	0.629	0.675

4. Conclusions

In ironmaking the amount of Zn which is recycled with the residues is limited to avoid operational problems in the BF. Therefore, not all the dusts generated can be recycled. Usually, the dusts from the dust catcher and the cast house dust are recycled via the sinter plant, while the residue from second stage top-gas de-dusting has to be fully or partly discharged. By application of air classification of the dusts the fraction of the recycled dusts can be increased while keeping the amount of Zn in the recycled dust constant.

For maximization of the recycled fractions of the dusts the Zn content in the coarse fraction as a function of the mass fraction of the coarse material is required for each dust. From the data gained in air classification experiments approximation functions for this dependence can be derived.

Generally, the positive effect of air classification was higher at lower values of the limit for the amount of Zn recycled with the dust. Depending on the value of the limit, the calculated possible increase in dust recycling was in the range of 0.27 to 0.45 kg/t HM for air classification of the second stage filter dust and the cast house dust, compared to classification of the second stage filter dust only. When all three dusts are classified the possible increase in dust recycling ranged from 0.35 to 0.79 kg/t HM.

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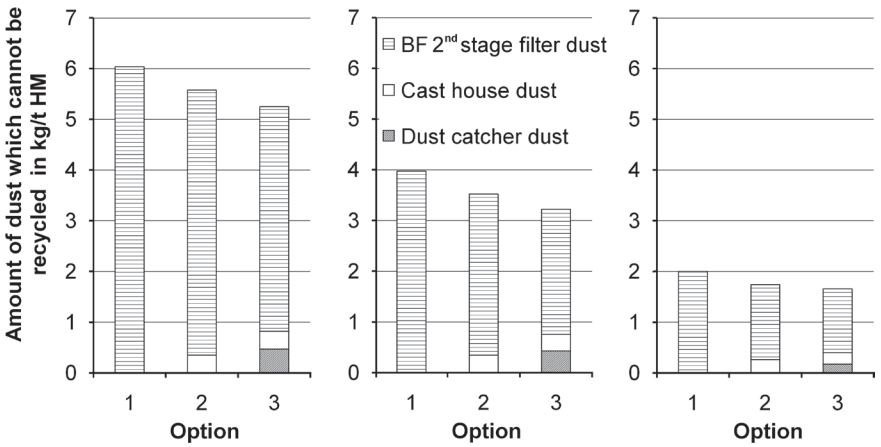

Fig. 5. Amount of dust which cannot be recycled to the sinter plant for various limits for the amount of Zn recycled (left: 40 g/t HM; middle: 60 g/t HM; right: 80 g/t HM).

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