Recycling of Sludge and Dust to the BOF Converter by Cold Bonded Pelletizing

Fenwei SU, Hans-Olof LAMPINEN and Ryan ROBINSON

SSAB Tunnplåt AB, SE-971 88 Luleå, Sweden. E-mail: fenwei.su@ssab.com
1) Luleå University of Technology, 971 87 Luleå, Sweden.

(Received on September 29, 2003; accepted in final form on December 3, 2003)

With the aim to increase the recycling of fine sludge and dust disposed normally in landfill, cold bonded pelletizing of the sludge and dust using cement as binder was investigated in laboratory scale as well as in the pilot scale pelletizing plant. The influence of BF flue dust, BOF fine sludge and oily mill scale sludge on the cold strength, capacity and reduction degree of cold bond pellets was studied experimentally on the basis of a statistical procedure. With a coarser representative particle size, oily mill scale sludge has the greatest effect on the cold strength. BF flue dust has a negative effect for increasing both the cold strength and capacity for levels of over 25% of the mixture. The BOF fine sludge has the positive effect on cold strength, while its interaction with BF flue dust has the negative effect on reduction degree.

The results of pelletizing tests in pilot scale show that the maximum cold strength (TTH 94 %) and capacity (13–15 t/h) of products is obtained at the conditions given by the optimal mixture design and cure time. The industrial tests on charging cold bonded pellets as burden material in the BOF converter were described. The charging weight of cold bonded pellets varied from 0.5 to 2.5 tons. The results of industrial tests indicated that the converter process was not subject to any adverse disturbances due to the addition of 2.5 tons of cold bonded pellets.

KEY WORDS: dust; sludge; recycling; cold bonded pellets; pilot scale tests; industrial tests.

1. Introduction

The recycling and utilisation of iron-bearing by-products such as dust, scale and sludge has long been promoted in iron and steel-making industry due to its several benefits: (i) to reduce the depletion of the earth’s limited natural resources; (ii) to reduce pollution produced by discharging untreated waste; and (iii) to save energy indirectly. The recycling of dust and sludge generated in integrated steel plants currently can be realized by using one or two of five methods, which include sintering, cold bonded agglomeration, injection, direct reduction (DR) and smelting reduction (SR).1−5 The choice of these methods, however, depends on several important factors such as the environmental requirements, energy policy, company’s statues, company’s strategies in recycling, feasibility concerning economy and technology.5,6 The ferrous burden in the blast furnace at SSAB Tunnplåt consists of 100% pellets due to the fact that the sinter plants were closed down in 1978 in Luleå for environmental reasons. As an alternative process, cold bond briquetting was proven to be a viable technique, attractive both economically and environmentally for recycling by-products.7,8 The cold bond briquette plant at SSAB Tunnplåt in Luleå was started in 1993, and since then most of the iron-bearing by-products have been recycled through the blast furnace by cold bonded briquetting. At present about 60 kg of briquettes/thm, which means around five percent of the total burden material, are charged into BF.9 This limit depends on several variables, such as the properties of by-products, the zinc content of materials, the strength of the cold bond briquette and the reduction conditions.

The studies reported in the literature and our investigations indicate that cold bonded pelletizing is considered to be the process most recommended for recycling fine dust and sludge from the comprehensive viewpoint of technical, economic and environmental aspects.8−12 The objective of the work presented in this paper is to increase the recycling of fine sludge and dust disposed normally in landfill by developing cold bond pelletizing technology. In this paper, the development and application of the cold bonded pelletizing are reviewed briefly, the influence of by-products, i.e., BF flue dust, BOF fine sludge and oily mill scale sludge on the cold strength, capacity and reduction degree of cold bond pellets was studied on the basis of a statistical procedure. Additionally, pilot scale pelletizing tests with an optimum mixture design for the BOF converter are described and the results of industrial tests on charging cold bonded pellets as burden material in the BOF converter are presented.
2. Development of the Cold Bonded Pelletizing

2.1. History and Application of Cold Bonded Pelletizing

The idea of cold bonded pelletizing of fine iron ores originated in Sweden, where K. J. V. Svensson applied for a Swedish patent.\(^{10}\) Cold bonded pelletizing has some specific features in contrast to the traditional pelletizing of iron ores. It consists of (i) material blending with binder (cement) at lower temperatures; (ii) bailing of fines under normal atmospheric conditions and (iii) pellet self-hardening at room temperature or at 70–100°C with a relative moisture of 70%.

The first cold bonded pelletizing plant was put into operation at Grängesberg, Sweden in 1971 for the agglomeration of fine iron ores.\(^{11}\) Since then, the cold bonded pelletizing method has aroused great interest in the world not only for treatment of iron ores but of other minerals as well. The cold bonded pelletizing related patents and know-how in the industry were developed further in some countries.\(^{12,14}\) Japan in particular.\(^{15,16}\) In the 1980’s it became evident that cold bonded pelletization was an economically feasible method for agglomerating iron ore fines and in particular, recycling of dust and sludge.

2.2. Factors Effecting the Properties of Cold Bonded Pellets

The factors effecting the properties and capacity of the cold bonded pelletizing can usually be classified as three types: raw materials (by-products and binder), manufacturing techniques, and the requirements of metallurgical properties.\(^{9,16}\) A summary of factors affecting cold bonded pelletizing is shown in Fig. 1. 

According to current thinking, the vital metallurgical properties of the constituents of a BOF converter burden are those: i) Chemical composition of material such as Fe, C, S and P; ii) mechanical strength and porosity of pellets; iii) reducibility and thermoplastic properties. Thus, the above parameters should not be neglected when assessing the properties of cold bonded pellets.\(^{17}\) Mechanical strength is an important property of cold bonded pellets, as the pellets must often be transported in the steel plant and must be resistant to compression and degradation caused by breakage on handling. The properties of cold bonded pellets depend greatly on the chemical and mineralogical composition, and physical state, of the material as well as the production technologies. The by-products are considered to be very important and variable factors due to the change of chemical composition and particle size distribution.

2.3. Theoretical Considerations

In consideration of the importance of the cold strength of cold bonded pellets, the bulk of the work is being carried out on the basis of agglomeration theories to determine the binding mechanisms and the cohesive forces involved in the process. The binding mechanisms of agglomeration were first defined and classified by H. Rumpf and his co-workers.\(^{9,16}\) A general formula describing the tensile strength of agglomerates, which are held together by binding mechanisms acting at the coordination points, is given as follows:\(^{18}\):

\[
P = \varphi \frac{1 - \varepsilon}{\delta} f(\delta) f(d)................... (1)
\]

where \(P\) is the tensile strength of agglomerates, \(d\) is the particle size of material, \(\delta\) is the wetting angle, \(\varphi\) is the coefficient of pores filled with water, and \(\varepsilon\) is the porosity. The porosity is calculated using the difference between the true density and apparent density:

\[
\varepsilon = (1 - \rho_a/\rho_t) \times 100 \text{ (\%)} .................. (2)
\]

where \(\rho_a\) is the apparent density, and \(\rho_t\) is the true density.

According to the Eq. (1), the tensile strength of agglomerates rises with increasing surface tension and with decreasing porosity and grain size values. The equation shows that sufficient strength can be obtained in such cases by selecting a suitable binding mechanism featuring high adhesion or binding forces, using a powder with a small representative particle size, applying suitable curing techniques that produce permanent bonds with high strength, and incorporating temporary additives in the feed.

3. Experimental

3.1. Materials

The dust and sludge used for the experimental studies were taken from SSAB Tunnplåt in Luleå and the cement was taken from LuleFrakt Brikett AB. All materials were sub-sampled respectively into 1–2 kg batches with a rotating splitter and stored in a cool, dry place. Table 1 shows the chemical analysis of the materials used for the experimental studies and the pilot scale production of cold bonded pellets charged into the BOF converter. As shown in Table 1 the sludge and dust are primarily composed of iron oxide (20–60%), and the remaining main components were CaO, MgO, SiO\(_2\) and Al\(_2\)O\(_3\). Except for BF flue dust and BOF coarse sludge, the chemical composition of all other materials are stable in metal oxide forms.

The results of particle size measurements show that the materials are coarser with ascending order as follows: cement<BF flue dust<BOF fine sludge<BOF coarse sludge<oily mill scale sludge

The cement has a fineness of 97% passing 32 \(\mu\)m, which was determined by laser diffraction. The particle size of BF...
flue dust is about 80% passing 250 μm and the other materials have a wide range of particle size distributions.

3.2. Test Procedure

A 20-kg sample that consists of by-products and cement was mixed in a drum mixer for 4 min and then the blend was emptied into a container and was mixed further with 12.5–13.5% water for another 2 min. After mixing again and sitting for 20 min, the pellet mass was fed into the disc pelletizer that was run with a rotating speed of 18 rpm at an angle of 45°. The pellet mass was left to rotate in the pelletizer for 20 min. The newly rolled pellets were spread out onto the floor for 1 h and then stored for an additional 24 h before sieving. The pellets with a size fraction of 9–12.5 mm were used in the test evaluation.

3.3. Test Evaluation

The test evaluation criteria applied were the tumbler handling strength of cold bonded pellets (TTH), the abrasion handling strength (ATH), the capacity and the reduction degree of pellets with size fraction 9–12.5 mm. The tumbler handling strength of cold bonded pellets is the main quality index used in the iron and steel-making industry. The tumbler handling strength index (TTH) is an international standard method in metallurgical production and these tests were carried out at LKAB. The TTH apparatus is a 100 cm wide cylindrical drum that, loaded with 3 kg of pellets sample with size fraction 9–12.5 mm, is rotated at a standardized speed and time. The pellets and fines are captured after tumbling and then sieved to fractions of $\frac{1}{6}$ mm and $\frac{1}{0.5}$ mm. The wt% of the $\frac{1}{6}$ mm fraction is recorded as the TTH value and the $\frac{1}{0.5}$ mm fraction as the ATH value. A related statistical procedure was used to conduct reduction experiments in inert gas over a temperature range of 20–1200°C.

3.4. Variables Examined and Design of Tests

The influence of BF flue dust, BOF fine sludge and oily mill scale sludge on the strength and capacity of cold bond pellets was studied experimentally. The amount of BOF sludge, BF flue dust and oily mill scale sludge were examined while other by-products and cement as well as pelletizing operation variables were kept constant. Experimental details of these groups of tests are presented in Table 2; each group was designed with a specific purpose.

By using the same reference recipe, the preliminary tests TP1, TP2 and TP3 were designed to judge the pelletizing time intervals by comparing the capacity of pellets with the size fraction 5–12 mm. Tests TP4 and TP5 were used to test the reproducibility of the results for a pelletizing time of 20 min. Taking into account the amounts of sludge and dust normally sent to landfill and the burden requirements of the converter, full factorial experiments (L1–L11) were designed to examine the effect of by-products; BOF sludge, BF flue dust and oily mill scale sludge, on the cold strength and capacity of cold bonded pellets to be charged into the BOF converter.

4. Experimental Results and Discussion

4.1. Effect of Dust and Sludge on the Strength and Capacity of Cold Bonded Pellets

According to our previous studies based on full factorial design tests, the interaction between BF flue dust and BOF fine sludge was considered to have a negative effect on the cold strength and capacity of cold bonded pellets at 20°C. The separate effects of BOF fine sludge and BF flue dust on the cold strength and capacity, however, were less negative. Table 3 shows result of factorial design tests, L1 to L11. The three factors are, A: BOF fine sludge with two levels, A1 (0 wt%) and A2 (20 wt%); B: BF flue dust with two levels, B1 (20 wt%) and B2 (30 wt%); and C: oily mill scale
sludge with two levels, C1 (0 wt%) and C2 (10 wt%). The level ABC (cpt) means the central point test for the three factors. The estimated effects of each factor for cold strength are shown in Fig. 2. The effect of a factor is defined as:

\[ \text{effect} = \frac{\text{mean response at high level}}{\text{mean response at low level}} \]

It is clear from Fig. 2 that oily mill scale sludge has the greatest effect on the cold strength at 20°C. The interaction between oily mill scale sludge and BOF fine sludge is also significant for cold strength in comparison with the factors BF flue dust and the interaction between oily mill sludge and BF flue dust. These results agree with the theory of Eq. (1), indicating that with a coarser representative particle size, oily mill scale sludge is a dominant factor for decreasing the cold strength. Therefore, the pre-treatment of oily mill scale sludge by using rod grinding should be considered in the further tests for decreasing the effect of the coarser particle on the cold strength of cold bonded pellets. In general, an optimal recipe with sufficient cold strength and metallurgical requirements can be obtained in such cases by selecting a suitable percentage of binder and by products with a small representative particle size, and applying suitable curing techniques. Test L9 in Table 3 is considered an optimal recipe due to the high TTH and capacity values.

4.2. Effect of Dust and Sludge on the Reduction of Cold Bonded Pellets

TG/DTA/MS experiments were run, using a Netzsch STA 409C furnace and a Balzers QMG 422, on the cold-bonded pellet batches L1–L11 to evaluate the effects of composition on reduction characteristics. Micro pellets from the −5 mm fraction for batches L1–L11 were heated from 20 to 1200°C in an Argon gas environment. The heating rate was 10°C/min and a mass spectrometer was used to analyze the gas that evolved from the sample pellets. The weight loss from heating for each pellet batch is given in Table 4.

The reduction of these pellets, in inert gas, is nearly complete at 1200°C. A representative diagram of the information attained from these reduction experiments is given in Fig. 3. Reactions taking place during heating are similar for pellet batches L1–L11. Endothermic reactions occur at −120, −450, −550, −700, −1050°C evolving H2O/H2 and CO/CO2 gas mixtures. It is assumed that some initial evaporation/dehydration and ensuing reduction is occurring.

A comparison of the effect of different factors on the reduction degree of pellets is given in Fig. 4. The results from the statistical evaluation in Fig. 4 show that the interaction between BOF fine sludge and BF flue dust (BOF*BF) has the largest negative effect on reduction degree and BOF fine sludge has the largest positive effect on reduction degree. One goal of the ongoing research is to find a blend of these factors that give an optimal relation between cold strength and reduction characteristics.

Table 4. The weight loss from heating for each pellet batch.

<table>
<thead>
<tr>
<th>Test No.</th>
<th>L1</th>
<th>L2</th>
<th>L3</th>
<th>L4</th>
<th>L5</th>
<th>L6</th>
<th>L7</th>
<th>L8</th>
<th>L9</th>
<th>L10</th>
<th>L11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wt. loss %</td>
<td>26.7</td>
<td>30.1</td>
<td>30.5</td>
<td>29.3</td>
<td>28.4</td>
<td>32.4</td>
<td>32.5</td>
<td>29.3</td>
<td>31.4</td>
<td>32.7</td>
<td>23.2</td>
</tr>
</tbody>
</table>

Fig. 2. Effects of factors BOF (BOF fine sludge), BF (BF flue dust) and Mil (Oily mill scale sludge) on the cold strength of cold bonded pellets.

Fig. 3. TG/DTA diagram for pellet batch L9.
5. Cold Bonded Pelletizing Tests in Pilot Scale

Pelletizing tests in pilot scale for BOF pellets were carried out at the LuleFrakt Brikett AB in 2001 and an amount of 74 tons of pellets were produced. The same pilot scale tests with an upgraded recipe (excluding BF dust) were carried out in 2002 and an amount of 300 tons of pellets were produced.18) A test procedure was described in an earlier paper. 17)

During the pilot scale tests, the pellet mass was fed by transport band to a disc pelletizer after material mixing, and then the produced pellets were sent to a rolled screen. The pellets with particle size greater than 10 mm were sent to a container by tractor. The pellets with particle size less than 10 mm were sent back to the disc pelletizer by transport band.

The recipe R1, based on lab test L9 and recipe R2, excluding BF flue dust, were used in the pilot scale pelletizing tests. Table 5 shows some results of the pilot scale pelletizing test in 2001 and in 2002, which indicates that the cold strength (TTH values) for all tests were more than 94% after 24 h, while the capacity of pellets was about 12–15 t/h. Table 6 shows the chemical analysis of cold bonded pellets in 2001 and in 2002, indicating that there is relatively little difference in chemical composition except sulphur content.

6. Industrial Tests on Charging Cold Bonded Pellets as Burden Material in the BOF Converter

The first group of industrial tests on charging cold bonded pellets as burden material in the BOF converter were carried out at the NO. 2 converter of SSAB Tunnplåt AB in 2001. Two reference tests without cold bond pellets and eight tests with cold bond pellets were conducted. The desulfurized hot metal is poured into the converter after charging scrap, and then the cold bonded pellets are charged. The charging weight of cold bonded pellets varied from 0.5 to 2.5 tons. Table 7 shows the results of industrial tests, No's J6396 to J6485, indicating that the contents of carbon, phosphorus and sulphur in the steel product, from the pellet tests, are close to the results from reference tests.

Table 8 shows the comparison of sulphur content in liquid metal, before and after the LD converter.

Table 5. TTH and capacity of BOF pellets in pilot scale tests in 2001 and 2002.

Table 6. Chemical analyses of pellets in pilot scale pelletizing tests for BOF converter in 2001 and in 2002.

Table 7. The results of industrial tests on charging cold bonded pellets (0.5–2.5 t) as burden material in the BOF converter (114 t) in 2001.

Table 8. Comparison of sulphur content in liquid metal, before and after the LD converter.

5. Cold Bonded Pelletizing Tests in Pilot Scale

Pelletizing tests in pilot scale for BOF pellets were carried out at the LuleFrakt Brikett AB in 2001 and an amount of 74 tons of pellets were produced. The same pilot scale tests with an upgraded recipe (excluding BF dust) were carried out in 2002 and an amount of 300 tons of pellets were produced.18) A test procedure was described in an earlier paper. 17)

During the pilot scale tests, the pellet mass was fed by transport band to a disc pelletizer after material mixing, and then the produced pellets were sent to a rolled screen. The pellets with particle size greater than 10 mm were sent to a container by tractor. The pellets with particle size less than 10 mm were sent back to the disc pelletizer by transport band.

The recipe R1, based on lab test L9 and recipe R2, excluding BF flue dust, were used in the pilot scale pelletizing tests. Table 5 shows some results of the pilot scale pelletizing test in 2001 and in 2002, which indicates that the cold strength (TTH values) for all tests were more than 94% after 24 h, while the capacity of pellets was about 12–15 t/h. Table 6 shows the chemical analysis of cold bonded pellets in 2001 and in 2002, indicating that there is relatively little difference in chemical composition except sulphur content.

6. Industrial Tests on Charging Cold Bonded Pellets as Burden Material in the BOF Converter

The first group of industrial tests on charging cold bonded pellets as burden material in the BOF converter were carried out at the NO. 2 converter of SSAB Tunnplåt AB in 2001. Two reference tests without cold bond pellets and eight tests with cold bond pellets were conducted. The desulfurized hot metal is poured into the converter after charging scrap, and then the cold bonded pellets are charged. The charging weight of cold bonded pellets varied from 0.5 to 2.5 tons. Table 7 shows the results of industrial tests, No's J6396 to J6485, indicating that the contents of carbon, phosphorus and sulphur in the steel product, from the pellet tests, are close to the results from reference tests.

Table 8 shows the comparison of sulphur content in liquid metal, before and after the LD converter.
the results from reference tests. In general, the converter process was not subject to any adverse disturbances due to the addition of cold bonded by-product pellets.

A second group of industrial tests on charging cold bonded pellets as burden material in the BOF converter were carried out respectively at the No. 1 converter and No. 2 converter of SSAB Tunnplåt AB in 2002. The desulphurized hot metal is poured into the converter after charging pellets and scrap. The charging weight of cold bonded pellets was 2.0 tons. A total amount of about 300 tons of cold bonded pellets were used in the tests.

Table 9 shows some of the results of both the 1st and 2nd industrial tests regarding the effect of charging cold bonded pellets on the amount of sludge generated in the BOF converter.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Pellets, t</td>
<td>0</td>
<td>2.5</td>
<td>2.5</td>
<td>0</td>
<td>2.0</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>Fe</td>
<td>23.2</td>
<td>22.3</td>
<td>20.6</td>
<td>18.62</td>
<td>15.04</td>
<td>15.19</td>
<td></td>
</tr>
<tr>
<td>CaO</td>
<td>35.5</td>
<td>36.3</td>
<td>38.1</td>
<td>45.57</td>
<td>43.41</td>
<td>45.16</td>
<td></td>
</tr>
<tr>
<td>MgO</td>
<td>11</td>
<td>13.2</td>
<td>14.5</td>
<td>10.75</td>
<td>12.87</td>
<td>10.6</td>
<td></td>
</tr>
<tr>
<td>MnO</td>
<td>4.42</td>
<td>4.21</td>
<td>3.65</td>
<td>3.88</td>
<td>3.7</td>
<td>3.3</td>
<td></td>
</tr>
<tr>
<td>SiO2</td>
<td>7.55</td>
<td>7.49</td>
<td>7.92</td>
<td>7.3</td>
<td>11.9</td>
<td>12.5</td>
<td></td>
</tr>
<tr>
<td>Al2O3</td>
<td>3.03</td>
<td>1.75</td>
<td>1.61</td>
<td>0.74</td>
<td>1.46</td>
<td>0.97</td>
<td></td>
</tr>
<tr>
<td>P2O5</td>
<td>0.66</td>
<td>0.67</td>
<td>0.58</td>
<td>0.58</td>
<td>0.58</td>
<td>0.58</td>
<td></td>
</tr>
<tr>
<td>V2O5</td>
<td>4.7</td>
<td>4.8</td>
<td>5.2</td>
<td>4.8</td>
<td>5.2</td>
<td>5.2</td>
<td></td>
</tr>
</tbody>
</table>

Table 9. Some test results regarding effect of charging cold bonded pellets on the composition of the slag produced in the BOF converter in 2001 and 2002.

Fig. 5. The effect of charging cold bonded pellets on the amount of sludge generated in the BOF converter.

Fig. 6. The effect of charging cold bonded pellets on the composition of slag produced in the BOF converter.

a. Industrial tests at No. 1 Converter in 2001
b. Industrial tests at No. 1 Converter in 2001
c. Industrial tests at No. 1 Converter in 2002
d. Industrial tests at No. 2 Converter in 2002
bonded pellets on the composition of the slag produced in the BOF converter. Further information is given in detail in Fig. 6, which indicate that chemical composition of slag is stable with and without addition of cold bonded pellets for both the 1st and 2nd industrial tests.

In general, similar to the results in 2001, the results of the second group of industrial tests in 2002 indicated that the converter process was not subject to any adverse disturbances due to the addition of cold bonded by-product pellets, except for some minor boiling problems.

In fact, the boiling that occurs in the BOF converter depends on many factors such as the size of scrap material, the quality of hot metal, amount of pellets, and other operating conditions as well. Thus, it is obvious that there is a need to conduct tests on charging cold bonded pellets as burden material in the BOF converter under pre-chosen conditions.

7. Conclusions

The results from batch tests in lab show that with a coarser representative particle size, oily mill scale sludge has the greatest effect on the cold strength. The BOF fine sludge has the positive effect, while its interaction with BF flue dust has the negative effect on reduction degree. An optimal recipe with higher capacity and cold strength for cold bonded pellets was obtained under given conditions.

The pelletizing tests in pilot scale with an optimum pellet recipe for the BOF converter were carried out. The results show that the cold strength of cold bonded pellets is higher than 94% after a curing time of 24 h with a capacity of 13–15 t/h at given conditions. According to the results of industrial tests on charging cold bonded pellets as burden material in the BOF converter, there are no adverse disturbances to the converter process due to the addition of cold bonded by-product pellets.

Acknowledgements

The authors would like to express their thanks to Lena Sundqvist-Öqvist and Dag Bergqvist, SSAB Tunnplåt AB, and Caisa Samuelsson and Bo Lindblom, Luleå University of Technology, for their suggestions and assistance in the course of the lab and industrial tests.

REFERENCES