Optimisation of the Slag Formation in a Blast Furnace Charged with 100% Pellets

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Preface

It seems that the blast furnace process will still be the predominant iron-making process in the future. SSAB Tunnplåt in Luleå has recently, in August 2000, started up a new blast furnace that replaces the two old smaller ones. The production capacity of BF No.3 is higher than the combined production capacity of both BF No.1 and No.2. However, a very high productivity and improved blast furnace performance was achieved for BF No.2. These good production results are mainly attributable to the use of olivine pellets, MPBO and KPBO produced at LKAB (a Swedish pellet producer) in Malmberget and Kiruna. The pellets have a low gangue content and good softening and melting properties in terms of a high melting point and a narrow softening and melting interval at varied pre-reduction degrees of the pellets. The high coke quality also contributes to the good results.

Since 1985, pulverised coal injection has been used at SSAB in Luleå and to further increase the coal injection rate a new facility for coal injection was put into operation in 1998. At approximately the same time a new oxygen plant operated by AGA Gas was also started up. This made it possible to increase the coal injection rate even more and also increase productivity.

A new self-fluxed pellet was under development at LKAB during the nineties. By increasing the iron content and decreasing the gangue content this pellet would make it possible to further improve the hot metal production efficiency in the Swedish blast furnaces. Metallurgical tests showed that the self-fluxed pellets had a higher reducibility, a narrower softening and melting interval, but lower melting temperature compared to the olivine pellets. Contrary to what was expected, the self-fluxed pellet made smooth BF operation difficult with problems including low permeability of the burden column, problematic tapping and irregular composition of final slag, which in turn indicated slag formation problems. The final slag itself varied in composition and the Al₂O₃ content reached high values from time to time. It is probable that the very low slag amount of 120 kg/thm resulted in slag formation problems in the bosh, where the fluxes were dissolved into the primary slag of the pellets producing a bosh slag with high basicity. The high melting point of the bosh slag increased even more, when the slag was further reduced and the slag reached its final composition [2].

To make it possible to use this self-fluxed pellet Ma [2] proposed injection of fluxes through the tuyeres. A low bosh slag amount can be achieved if the excessive basicity of the bosh slag is avoided and as a result the energy consumption will decrease, the productivity increase and the amount of final slag can be kept very low. The slag formation process will be smoother and local variations in basicity will decrease.

This work is part of the “Injection of fluxes into the blast furnace” project and also part of the research program at SSAB. The studies carried out will clarify some phenomena of slag formation in the blast furnace including the effect of:

a) basic fluxes on slag formation in the blast furnace, if they are top charged
b) basic fluxes on slag formation in the blast furnace, if they are tuyere injected
c) the chemical composition of pellet and fluxes
d) reduction behaviour and softening and melting properties of the pellets
e) the reduction degree of pellets
f) the reduction conditions (reduction temperature, reducing gas composition)
This thesis is based on the results published in the following papers:


Abstract

Charging with olivine pellets, produced by LKAB in Malmberget and Kiruna in the north of Sweden, has contributed to very acceptable performance of the blast furnaces of SSAB Tunnplät in Luleå. The pellets have, in general, a stable reduction behaviour, a low gangue content and a very narrow softening and melting interval. However, increased proportions of coarse pellets as a result of, for example, segregation at low filling levels in pellet bins result in changed metallurgical properties—the reduction behaviour and the softening and melting properties are changed. This has caused severe disturbances in the blast furnace process on several occasions. These disturbances included low gas utilisation, large variations in permeability of burden column, large variations in heat load, low hot metal temperature, low chemical energy of hot metal and series of slips. The reason for changed blast furnace performance when charging with an increased amount of coarse pellets was verified in pilot scale tests at the LKAB pilot blast furnace (hereafter called PBF) at MEFOS (Metallurgical research centre in Luleå). Laboratory tests showed that the disturbances could be attributed to different properties of the coarse pellets compared to those of normal-size in terms of a lower porosity and a higher amount of residual magnetite in oxidised pellets. This results in, for example, a high residual content of FeO in the pellet core, a higher degree of disintegration and swelling during reduction, and increased width of the softening and melting temperature interval.

In order to achieve even better performance of the blast furnace, a new type of self-fluxed pellet with a low gangue content has been under development. The pellets have quite good metallurgical properties [27] such as a high reducibility and a narrow softening and melting temperature interval. However, industrial trials using this type of self-fluxed pellets have not shown any improvement of the blast furnace performance. On the contrary, difficulties arose concerning the smooth regulation of the blast furnace operation, such as low permeability of the burden column, problematic tapping etc. One of the reasons has been theoretically attributed to a problematic slag formation process in the furnace [2]. The pellet itself has an early melting slag, but, when top charging self-fluxed pellets together with basic flux, an excessive basic slag can form in the cohesive zone, where the top-charged basic fluxes partly dissolve into the primary slag of the pellets. The newly formed slag can have a very high melting point and a low fluidity, which can even result in the re-solidification of the slag. The melting properties of the FeO rich slag will be even poorer, when it is further reduced and the FeO content decreases. As a result, the permeability of the cohesive zone and of the bosh region is decreased. A proposal to inject basic flux via the tuyeres instead of top charging them has also been made to enhance the slag formation process at very low slag volumes and therefore the blast furnace operation.

The effect of the degree of reduction, and the interaction between the slag formers and pellets in the lower part of the shaft and in the cohesive zone of the blast furnace, were studied. Based on a proposal to inject flux into the blast furnace via tuyeres, laboratory tests of the softening and melting properties of four types of LKAB pellets, with and without additional flux, corresponding to the bosh slag formation, have been carried out. Melting point measurements of coke and coal ashes, with and without addition of basic flux, corresponding to the tuyere slag, have also been performed. Chemical analyses, melting point measurements and morphological studies were also carried out on samples from the laboratory softening and melting tests as well as on samples from the LKAB PBF at MEFOS. The softening and melting point of the pellets increased and the width of the softening and melting temperature interval decreased with increased reduction degree of the pellets. When the pellet diameter is increased the amount of residual wustite in the core increases, resulting in a decreased softening temperature and an increased melting temperature and consequently the width of the softening and melting temperature interval is increased. The test results showed that the additional basic fluxes could improve softening and melting properties of olivine pellets to a certain extent, but significantly deteriorate the melting properties of self-fluxed
pellets. The results indicate that interaction between olivine pellet and BOF slag may cause variations in slag composition and slag properties at different levels in the blast furnace as well as at different radial positions, especially with uneven distribution of fluxes. The basic fluxes probably caused the deteriorated melting properties of fluxed pellets by formation of a high basicity slag in the bosh. The negative effect on slag formation caused by top charged fluxes is avoided by injecting fluxes through the tuyeres. Injection of fluxes will improve melting properties of the tuyere slag considerably.
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1. INTRODUCTION

1.1 Background

The blast furnaces at SSAB Tunnplåt AB in Luleå have been charged with a 100% pellet burden since 1978. Pellets with a high Fe content produced by the Swedish pellet producer—LKAB in Kiruna and Malmberget—are used present. They have good metallurgical properties in terms of high softening and melting temperatures and a narrow softening and melting temperature interval. The pellet quality has contributed to a very high productivity, a low slag rate, a low consumption of reducing agents and good blast furnace performance. To improve the productivity and decrease the consumption of reducing agents further, new pellet types are under development. One new lime-quartzite based self-fluxed pellet was tested at SSAB Tunnplåt in Luleå in 1994. The pellet had a high reducibility and a very low gangue content. When 100% of the self-fluxed pellet was used the slag volume was very low, approximately 120 kg/thm. However the BF process showed irregularities, the pressure drop increased and varied largely, the cooling effects in the lower part of the furnace increased and the chemical composition of the tapped slag varied considerably. The reason for these phenomena was problems with slag formation in the lower part of the furnace according to Ma [2]. When using pellets of a low gangue content the amount of the addition of fluxes will be quite low and problems in achieving an even distribution of the fluxes might occur. When the self-fluxed pellet with a basicity $B_2=\text{wt.}%\text{CaO}/\text{wt.}%\text{SiO}_2=1$ is used the fluxes that are supposed to be consumed by the coke ash will dissolve in the early melting bosh slag and increase the basicity as well as its melting point. The excessive basicity will be even higher than average because of an uneven distribution of the fluxes charged into the blast furnace. Ma proposed that fluxes should be injected through the tuyeres instead of being top charged to avoid the slag formation difficulties. In Figure 1 the basicity of primary slag, bosh slag, tuyere slag and final slag is compared for self-fluxed pellets with and without injection of BOF slag. The primary slag consists of the gangue content in the pellets. The bosh slag is considered to be formed by the primary slag, all additives and fluxes and some ash from the coke that is consumed. The ash released in the raceway when coal and coke are combusted forms the tuyere slag. The tuyere slag contains the constituents in flux or ore if they are injected. The bosh slag and tuyere slag are mixed and after some additional reduction of the mixed slag the final slag is formed. As can be seen, the excessive basicity of the bosh slag is avoided by the injection of fluxes.

1.2 Objectives

Injection of fluxes has been investigated in several studies with the intention of controlling the Si and S content of hot metal. The effect on the hot metal composition has been determined and the method of injection of fluxes has been developed. However, the possibility of controlling and optimising the slag formation by this technique has never been evaluated. In order to understand...
and evaluate the slag formation process in the blast furnace, and how it is influenced by top charging and tuyere injection of fluxes, a research project financed by Jernkontoret (The Swedish Ironmasters’ Association), Sweden, was started. Most of these studies are part of the project, "Injection into the blast furnace", but some aspects are included in the research programme at SSAB Tunnplåt in Luleå.

1.3 Literature Survey

1.3.1 Blast Furnace Process

Figure 2 shows the BF process schematically. At SSAB Tunnplåt in Luleå the ferrous burden, which consists of 100% olivine pellets produced at LKAB is charged at the top together with the fluxes. Between the pellet dumps coke is charged. At the top of the blast furnace the burden materials are lumpy and the gas permeability of the burden column is quite high. The charged materials are heated up and dried by the ascending gas and, when the temperature is high enough the limestone is calcinated. The coal and coke are combusted in the raceway and produce CO that indirectly reduces the iron oxides in the pellets [1][3].

\[
\text{Fe}_2\text{O}_3 + 3\text{CO} \rightarrow 2\text{Fe} + 3\text{CO}_2
\]

Figure 2. The blast furnace process.

**Top gas**

\((\text{CO}_2, \text{CO}, \text{N}_2, \text{H}_2)\)

**Blast:**

**Preheated air**

**Oxygen**

**Fuel**

**Flux**

**Coke**

**Pellet**

**Cohesive zone**

**Primary slag**

**Dripping zone**

**Bosh slag**

**Slag**

**Final slag**

**Raceway**

**Tuyere slag**

**Hearth**

**Hot Metal**

\[\text{CO}_2 \text{ reacts with the coke according to the Boudouard reaction.} \]

\[
\text{CO}_2 + \text{C} \rightarrow 2\text{CO}
\]

The burden materials soften and start to melt in the cohesive zone. The permeability of the pellet layers decreases and as a result the pressure drop is very high over this part of the furnace. The gas passes through the coke windows that distribute the gas over the blast furnace diameter. In the bottom of the cohesive layers the slag and metal start to drip. The dripping material flows through the coke. Carbonisation and desulphurisation of hot metal as well as homogenisation of slag and hot metal take place as the material flows down to the hearth [1][3].

Different types of slag are formed at different locations in the blast furnace. The primary slag consists of the gangue content in the pellets. The bosh slag is considered to be formed by the primary slag, all additives and fluxes and some ash from the coke consumed being dissolved into it. The ash released in the raceway when coal and coke are burnt, forms the tuyere slag. The tuyere slag contains the constituents in flux or ore, if they are injected. The bosh slag and tuyere slag are mixed and after some additional reduction of the mixed slag, the final slag is formed.

1.3.2 Tuyere injection

Tuyere injection of oil or natural gas and later on of pulverised coal has been practised at blast furnaces for a long time. The main reasons for injection of reducing agents are economical, increased coke demand as a result of increased hot metal production, but also because of the fact that the coke supply will decrease, as many of the coke plants are in the end of their lifetime. At SSAB Tunnplåt in Luleå coal injection was first installed in 1985. In 1998 a new coal injection plant was taken into operation. By increasing the coal injection rate from 80 to 160 kg/thm the
demand of external coke for the blast furnaces will be minimised and the main supply of coke will be accomplished by the existing coke plant at SSAB.

A high coal injection rate results in different phenomena in the blast furnace when compared to operation with low coal injection rates or "all coke" operation [8]. The burden distribution is changed to maintain the gas permeability of the blast furnace. The weight of the burden column increases and as a result the coke degradation is enhanced. The descendant rate of the burden in the upper part decreases and the heat flux ratio decreases, which will give an increased top gas temperature, an increased temperature of thermal reserve zone and an increased heat level of the blast furnace. By oxygen enrichment, these effects will be limited. Fines generation in the raceway might increase at high coal injection rates. The slag formed in the raceway when coal and coke are burnt, produces a tuyere slag of a very low basicity, B2=0.05. Especially at high coal injection rates a shell can be formed by ashes from pulverised coal combined with high melting slag in the end of raceway. The depth of the raceway is shortened, but it is vertically elongated. As soon as the shell is formed small coke particles will be trapped in it and the permeability of gas into the dead man is suppressed. The formation of a shell might be affected by the rate of ash supply and its dripping rate. The shell is not permanent, but when it is present the increased gas pressure will force the dripping liquid phase from the upper part towards the dead man. These phenomena will result in an increased and more varied pressure drop both in the upper and lower part of the blast furnace. The pressure drop will for example vary periodically with the level of hot metal and slag in the hearth [8].

The tuyere slag formed, when coal and coke are burnt, is as mentioned earlier very acid and has a high content of Al₂O₃ and SiO₂. The activity of SiO₂ is high in the tuyere slag and at the high temperatures in the flame zone SiO gas is generated. This is one important mechanism for siliconisation of hot metal. Reduction of SiO₂ in slag by C in the coke [1] is another mechanism for siliconisation of hot metal. This becomes important at temperatures above 1700°C. A lot of efforts have been made to understand the mechanisms for siliconisation of hot metal and thereby making it possible to decrease the silicon content.

Injections of fines of fluxes and iron oxide have been tested in some blast furnaces to decrease the Si content of hot metal [9][10][11][12][13][14]. In a study of simultaneous injection of coal and dolomite a significant effect on decreasing the Si content of hot metal was found [10]. The effect of adding material containing MgO from the top or by tuyere injection showed that the silicon content was decreased in both cases. However, the effect was higher when injecting the flux when compared to top charging it. The effect from top charging was more significant, if the flux was charged into the coke layers, compared to when it was mixed with ore [9]. The reason for injecting fluxes containing CaO and MgO is that the activity of SiO₂ in the tuyere slag is thereby decreased and followed by a decreased generation of SiO gas. The injection of iron ore powder only did not have any effect on the Si content of the hot metal, while a mixture of flux and iron ore did decrease the Si content [12]. In another study on injection of iron ore fines, it was found that the Si content was decreased. If sinter fines containing CaO was used the effect was higher [11]. When injecting a mixture of iron ore and coal fines or a water-slurry containing iron ore, a decreased silicon content of hot metal could be seen [13]. Injection of iron ore dust containing some CaO reclaimed from the storage bins of the blast furnaces had a significant effect in decreasing the Si content of hot metal. The report also states that it is important to depress the reduction of iron oxide. The different results achieved in the studies on injection of iron ore fines might be partly explained by the particle size of iron ore [14]. In the case of a very fine iron ore grain size the reduction in raceway will be efficient and the amount of residual FeO limited. The original oxidation degree of the slag in the bosh and the hearth is also important [12].
As injection of fluxes seems to be a possible technique, from the point of view of blast furnace operation it could also be used to control the slag formation both in the bosh and in the raceway. The low basicity of tuyere slag could be adjusted to get a slag of desired properties. The dripping of slag from the raceway might be enhanced and thereby the formation of a shell in the end of the raceway prohibited. This can improve the gas permeability into the dead man and the drainage of slag and metal formed in the bosh and in the raceway. The formation of high basicity slag in the bosh will be avoided as well. There will be no risk of re-solidification of the bosh slag, as the FeO content of the slag decreases.

1.3.3 Formation and properties of slag in the BF
As mentioned earlier the primary slag is considered to consist of the gangue content of the pellets and is affected by the components of the blast furnace gas for example its alkalis. Interaction with the other burden materials is not supposed to occur until the material enters the softening and melting zone.

The top-charged basic fluxes are neutralising the gangue of the pellet and the ashes of coke and coal. The main generation of ash occurs in the raceway, where the coal and coke are mainly combusted. This means that the fluxes present in the bosh region are excessive and that the slag formed here will have excessive basicity compared to the final slag. Examples of variations of basicities along the blast furnace height for two different pellet types can be seen in Figure 3 [2]. Their chemical compositions are stated in Table 1. An uneven distribution of fluxes might further increase this effect. The excessive basicity of the bosh slag is most pronounced, when the gangue content of the pellet is low and the ash content of coal and coke is quite high. The final slag with desired properties is formed when the bosh slag of excessive basicity is combined with the acid tuyere slag.

Analyses of operating problems at two English blast furnaces indicated that they were caused by the formation of a bosh slag with a composition containing the di-calciumsilicate phase. The slag had high liquidus temperatures and the effect of ferrous oxide was found to be dependent on the overall basicity – (CaO+MgO)/(SiO2+Al2O3) – of the slag [4].

Evaluation of operation, with a fluxed pellet with B2=1.26 and silicous ore as a basicity adjustment material every sixth charge, indicated slag formation problems in the dripping zone. Charging five pellet layers with a high basicity alternately with a very acid layer caused variations in the composition of the slags formed. In the high basicity layer a di-calciumsilicate containing highly viscous slag was formed. The liquidus temperature of this slag was so high that it also might have formed a solid phase. By exchanging the silicous ore for acid pellets, as a basicity controlling material, the variations in slag basicity decreased dramatically and the blast furnace operation became smoother. The temperature profile was changed and the cohesive zone moved by increasing the flame temperature and as a result the high basicity slag could melt and was prevented from solidifying.

Table 1. Chemical composition of two pellet types used for estimation of basicities along the height of the blast furnace.

<table>
<thead>
<tr>
<th>Sample</th>
<th>CaO</th>
<th>SiO2</th>
<th>MgO</th>
<th>Al2O3</th>
<th>FeO</th>
<th>TFe</th>
<th>CaO/SiO2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pellet A</td>
<td>1.39</td>
<td>1.43</td>
<td>0.39</td>
<td>0.33</td>
<td>0.44</td>
<td>66.94</td>
<td>0.98</td>
</tr>
<tr>
<td>MPBO</td>
<td>0.26</td>
<td>1.94</td>
<td>1.48</td>
<td>0.43</td>
<td>0.77</td>
<td>66.73</td>
<td>0.14</td>
</tr>
</tbody>
</table>

Figure 3. An example on the variation of average basicities along the height of the blast furnace.
from re-solidifying. When testing a pellet with $B_2=0.9$ the melting point of the slag formed after reduction of FeO was lower compared to pellets with $B_2=1.26$. This is an advantage, when the flame temperature for some reason cannot be increased. [5]

The viscosity of the bosh slag, the tuyere slag and the final slag are of great importance for blast furnace operation. If the viscosity increases, the amount of residual slag in the blast furnace will increase. The result will be a larger. If the viscosity of the final slag increases from 3.5 poise to 4.75 poise, the residual slag amount will increase by 14% [7]. Model experiments have shown that if the slag viscosity increases to a value over 6-10 poise, or if the void fraction of dead man decreases to less than 65% of initial void fraction the slag will no longer be able to flow through the deadman. It will instead flow between the blast furnace wall and the dead man [6].

1.3.4 Properties of blast furnace burden materials

Laboratory tests of reduction properties, as well as softening and melting properties of the pellets, are often carried out. These tests very often include only one type of ferrous burden material. However, if the behaviour in the blast furnace is to be predicted, it will be necessary to evaluate the mixture of all burden materials that are supposed to be combined in the burden mixture.

The reduction of pellets is dependent on the temperature profile of the blast furnace as well as the composition of the reducing gas. The pellet properties such as porosity, chemical composition and slag amount are very important too. The reduction proceeds topochemically. The shell will be well reduced and consists almost only of metallic iron, while the core still consists mainly of wustite. At reduction at higher temperatures, over 1100°C, the metallic shell and the slag phase formed might block the pores and inhibit further reduction. The retardation of reduction increases with increased slag amount and with decreased basicity of the pellets [1].

Important factors which affect the pressure drop in the blast furnace are the disintegration of ore during reduction and the shrinkage of the pellet bed on softening. If MgO is added to superfluxed pellets the disintegration will be decreased as a result of the formation of magnetite-magnesioferrite solid solution $(\text{MgFe}_{1-x}\text{O} \cdot \text{Fe}_2\text{O}_3)$. This phase is produced among the iron oxide grains and acts as a strongly bonding phase, and magnetite stabilised by MgO is hardly oxidised to hematite. At reduction temperatures above 1100°C the magnetite-magnesioferrite solid solution and calcium ferrites containing MgO are reduced to a wustite containing MgO. The softening properties of the pellets are improved, because the liquidus temperature of wustite is increased with increasing MgO content [1]. In the pellets used at SSAB Tunnplåt the MgO is added in the form of olivine. The MgO content has been found to improve the high temperature properties of the pellets by increasing the melting point of the slag phase and the wustite phase [22]. This effect will be especially important, if the pellet contains high amounts of residual magnetite after sintering. Coarse pellets have, for example, a higher content of residual magnetite compared to those of normal size. At reduction of magnetite a dense wustite phase is formed and further reduction is limited [23]. These negative effects on the high temperature properties in terms of decreased melting temperature will be limited by the MgO content of the wustite phase.

The melting and dripping characteristics of the pellets are dependent on the reduction degree and the chemical composition of the pellet. The melting point of the pellets increases with increased reduction degree. In this case the MgO content is also of great importance. For example, in one test, two samples consisting of different pellet types and a reduction degree of 50-60% were heated up to 1300°C. The slag and wustite contained in the core of the lime-fluxed pellets flowed out to the surface and partially filled the voids in the bed. However, the core of the pellets containing MgO did not melt and flow out, because during reduction MgO is concentrated to the magnesiowustite solid solution and the melting point of this phase rose. This means that when using pellets containing MgO the effect of different reduction degrees on softening and melting behaviour is
limited. The melting process of highly reduced pellets containing considerable amounts of metallic iron in the core is also affected by the ease of coagulation and separation of metal and slag. If the melting point of the slag matrix is quite low, the coagulation of metallic phase takes place easily [1][22].

Normally, tests of BF burden materials are performed with pellets in the size range of 10-12.5 mm. This makes it possible to compare the pellet properties of different types of pellets as well as for the same material from time to time. However, the properties of the pellets vary dependent on their size. This should be expected as the pelletizing process as well as the reduction reaction proceed topochemically. A change in blast furnace performance has been observed, when an increased ratio of oversized pellets is charged [15]. The dependence of pellet properties on the size has been shown in laboratory trials. The oversized pellets show a higher low temperature breakdown (LTB) and a lower reducibility compared to those of normal size [15][16][17]. The increased amount of residual FeO found in the cores will also have effect on the interaction with other burden materials such as fluxes, other pellets and coke.

The softening and melting properties of the blast furnace burden depend on the total burden composition. It can be expected that with pellets producing an early melting slag the dripping slag will come into contact with the other burden materials and have effect on their melting properties as well. The solid-solid reaction rate is probably low compared to the solid-liquid or liquid-liquid reaction rate.

When using pellets containing slag with a high melting point together with fluxes with a high melting point it could be expected that the reaction between the different burden materials would start at a considerably higher temperature. In some laboratory experiments, it was stated that if one aims to reduce the viscosity of the sinter slag by adding some acid material, it would be better to use some early-melting acid iron ore rather than silica with a very high melting point. When using the silica with a high melting point an excessive amount was needed compared to when using the more reactive acid ore [18].

Pieces of fluxes with a high melting point, such as dolomite and lime, have been found at tuyere level on excavation of quenched blast furnaces [19]. The fluxes take part in the slag formation in the cohesive zone, but, as their melting points are very high, residual material will be found in the hearth of the blast furnace. Residual lime has also been found in drilling coke cores from the LKAB PBF and in the hearth of the furnace on excavation

1.4 Scope of work
The scope of work and the content of different papers are summarised in Figure 4. The slag formation in the bosh part of the blast furnace has been investigated by general studies of the effect on softening and melting behaviour of olivine pellets, acid pellets and fluxed pellet by

- Reducing conditions (temperature, gas composition, time)
- Reduction degree (60, 75 and 90% degrees of reduction)
- Addition of fluxes (BOF slag, lime, dolomite)
- Particle size of pellets
A preliminary study concerning the reduction behaviour of different pellet types from LKAB and BOF slag from SSAB Tunnplät in Luleå have been done. Isothermal reduction tests have been performed at different temperatures in the range of 700 to 1200°C. The reducing gas compositions have consisted of 40% CO, 0-10% H₂ and N₂ up to 100%. The pre-reduction conditions for preparation of materials for softening and melting tests were chosen from the results from this preliminary study. The reducing gas composition used in pre-reduction was 40% CO, 5% H₂ and 55%N₂, tested at 800°C, 950°C and 1150°C.

The softening and melting behaviour of the different pellets and the effect of basic fluxes on this were tested in softening and melting laboratory tests. The softening and melting tests as well as the morphological studies of the test samples and samples from the PBF, have been used to partly explain the slag formation in the cohesive zone of the blast furnace.

The melting properties of tuyere slag have been studied with the aim of finding the effect of basic flux injection on tuyere slag properties. Melting point measurements of tuyere slag specimens based on the BF operational conditions of coal injection and injection of different levels of basic fluxes have been made. The fluxes tested are BOF slag, burnt lime and burnt dolomite.
2. Methodology

Based on the idea of injecting fluxes through the tuyeres of the blast furnace laboratory tests have been carried out in the areas of reduction, softening and melting and melting point measurements. Laboratory produced samples, probe samples and excavation samples taken from the LKAB PBF at Mefos have been studied morphologically in the optical microscope and by SEM. The studies made are summarised in Table 2. In addition to these studies, XRD, high temperature XRD, porosity measurements and a large number of chemical analyses have been made. Theoretical estimation of melting points has also been made. Part of the results have been evaluated to some extent and published in the three papers, contained in this thesis as appendices.

Table 2. Laboratory tests performed in the study.

<table>
<thead>
<tr>
<th>Reduction tests</th>
<th>Softening and melting tests</th>
<th>Melting point measurements</th>
<th>Morphological Studies Optical Microscope</th>
<th>Morphological Studies, SEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isothermal tests – pellet types</td>
<td>Pellet types – different reduction degree</td>
<td>Pellets of different reduction degrees</td>
<td>Reduced samples of different pellet types</td>
<td>Samples from softening and melting tests – pellets and BOF slag</td>
</tr>
<tr>
<td>Isothermal tests BOF slag</td>
<td>Pellet types – different reduction temperature</td>
<td>BOF slag of different reduction degrees</td>
<td>Reduced samples of different pellet fractions</td>
<td>Samples BF simulated softening and melting tests of pellet fractions</td>
</tr>
<tr>
<td>BF simulated tests BOF slag</td>
<td>BOF slag - different reduction degree</td>
<td>Excavation samples – pellets, BOF slag, dripping metal and slag</td>
<td>BOF slag of different reduction degrees</td>
<td>Probe samples - pellets</td>
</tr>
<tr>
<td>BF simulated tests – pellet fractions</td>
<td>Pellet fractions – different reduction degrees</td>
<td>Tuyere slag mixtures based on injection of BOF slag, burnt lime and burnt dolomite</td>
<td>Excavation samples – pellets and BOF slag</td>
<td></td>
</tr>
</tbody>
</table>

2.1 Experimental method

2.1.1 Laboratory tests

As can be understood from Table 2 laboratory equipment of different types has been used in the laboratory experiments. The main part of the tests has been performed at Luleå University of Technology and the equipment used is described in this section and in Paper 1. Some of the results, mainly presented in paper 3, were produced in laboratory tests performed using standard equipments at the metallurgical laboratory of LKAB in Malmberget and in a blast furnace model at Mefos [26].

2.1.1.1 Softening and melting tests

The experimental apparatus is shown in Figure 5. The furnace is heated electrically by U-shaped Super-Kanthal element with a heating zone about 800 mm in height. The highest working temperature is 1600°C. The crucible (40 mm i.d. x 85 mm height) made of graphite or alumina, as shown in Figure 6, has 6 holes each 6 mm in diameter in the bottom, allowing dripping of the molten materials and flow of gas through the sample bed. A balance with a container mounted on it was installed under the reaction tube for weighing the dripped materials.
The test samples were sandwiched between two layers of coke. Throughout the test, a constant load of 0.9 kg/cm² was applied to the sample bed by means of a pneumatic piston rod. The pressure delivered by the piston and a nitrogen gas flow through the sample bed were regulated via a computer – PC 1. The bed contraction, the pressure drop across the sample bed, and the weight of dripped materials as well as the temperature in the course of the experiment were measured with corresponding devices and recorded by the second computer – PC 2. After reaching the temperature desired, the sample was cooled down to ambient temperature. The whole process was protected by nitrogen gas, with a flow rate of 7 l/min. The experimental conditions used for softening and melting tests are summarised in Table 3.

**Table 3. Summary of test conditions**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample bed diameter</td>
<td>40 mm</td>
</tr>
<tr>
<td>Sample bed height</td>
<td>55 – 60 mm</td>
</tr>
<tr>
<td>Particle size</td>
<td></td>
</tr>
<tr>
<td>Pre-reduced pellets</td>
<td>9 – 13.5 mm</td>
</tr>
<tr>
<td>BOF-Slag, burnt dolomite and limestone</td>
<td>3 – 6 mm</td>
</tr>
<tr>
<td>Coke breeze</td>
<td>6 – 9 mm</td>
</tr>
<tr>
<td>Pellets weight of each test</td>
<td>~100 g</td>
</tr>
<tr>
<td>Nitrogen gas flow</td>
<td>7 l/min</td>
</tr>
<tr>
<td>Heating rate</td>
<td>200 °C/h</td>
</tr>
<tr>
<td>Pre-reduction degree of pellets</td>
<td>60, 75, 90, %</td>
</tr>
</tbody>
</table>

**Figure 5. Schematic view of experimental apparatus**

**Figure 6. Location of samples in the furnace tube**
For characterising the softening and melting behaviours of the samples, the following two indices have been used:

- \( T_1 \): a temperature, at which the pressure drop and the shrinkage of the sample bed start to increase sharply; it serves as the softening temperature in the tests made in this equipment. Figure 7 shows one example of this temperature for MPBO pellet;
- \( T_{sd} \): start-of-dripping temperature, at which the first droplet of the melting material dropped to the collector; it also stands for the melting temperature in the paper.

Four types of pellets, made at LKAB, were tested. The chemical analyses of these pellets as well as three types of fluxes, taken from SSAB, used in the study are shown in Table 4. Two types of self-fluxed pellets was tested, the former one has a slightly higher CaO content, but a lower MgO content than the latter one. MPBO and KPBO are olivine pellets with a similar chemical composition. They differ slightly from each other in CaO content.

Table 4. Chemical composition of the test samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>CaO</th>
<th>SiO₂</th>
<th>MgO</th>
<th>Al₂O₃</th>
<th>Fe₂O₃</th>
<th>FeO</th>
<th>TFe</th>
<th>CaO/SiO₂</th>
<th>CaO+MgO</th>
<th>SiO₂+Al₂O₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pellet A</td>
<td>1.33</td>
<td>1.33</td>
<td>0.35</td>
<td>0.32</td>
<td>95.63</td>
<td>0.44</td>
<td>67.23</td>
<td>1.00</td>
<td>1.26</td>
<td>1.28</td>
</tr>
<tr>
<td>Pellet B</td>
<td>1.22</td>
<td>1.31</td>
<td>0.76</td>
<td>0.38</td>
<td>95.16</td>
<td>0.55</td>
<td>66.99</td>
<td>0.93</td>
<td>1.51</td>
<td>1.59</td>
</tr>
<tr>
<td>MPBO</td>
<td>0.28</td>
<td>1.97</td>
<td>1.48</td>
<td>0.36</td>
<td>94.54</td>
<td>0.77</td>
<td>66.72</td>
<td>0.14</td>
<td>0.89</td>
<td>0.75</td>
</tr>
<tr>
<td>KPBO</td>
<td>0.40</td>
<td>2.15</td>
<td>1.47</td>
<td>0.23</td>
<td>94.77</td>
<td>0.37</td>
<td>66.57</td>
<td>0.19</td>
<td>0.87</td>
<td>0.78</td>
</tr>
<tr>
<td>BOF-slag</td>
<td>41.09</td>
<td>9.84</td>
<td>12.97</td>
<td>0.95</td>
<td>8.08</td>
<td>16.40</td>
<td>18.40</td>
<td>4.18</td>
<td>5.49</td>
<td>5.01</td>
</tr>
<tr>
<td>Burnt lime</td>
<td>91.99</td>
<td>2.09</td>
<td>1.80</td>
<td>1.08</td>
<td>0.58</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Burnt</td>
<td>52.74</td>
<td>1.41</td>
<td>38.41</td>
<td>0.35</td>
<td>0.35</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Samples of the self-fluxed pellets were pre-reduced to a 60, 75 and 90 % degree of reduction at 850°C and using 55%N₂-40%CO-5%H₂ as reducing gas. Cracks in the pellets during the reduction could be avoided to a large extent. Olivine pellets were pre-reduced to a 60, 75 and 90 % degree of reduction at a temperature of 950°C with the same reducing gases. Accordingly, BOF-slag used was also pre-reduced under the same conditions. As for the amount of BOF slag used, and its segregation in the blast furnace, additions of slag corresponding to 5% or 10% of the pellet weight were made to the samples. Three different distributions of BOF-slag in the pellet bed were used, as shown in Figure 8.

Figure 7. Definition of the softening temperature

Figure 8. Three different distributions of BOF-slag in pellet bed, a) layered pellets and BOF slag; b) even mixture; c) uneven mixture.
2.1.1.2 Melting point measurements

Figure 9 shows a schematic view of the high temperature microscope for measuring the melting point. The furnace is heated electrically and the highest working temperature that can be reached is 1640°C. A heating rate of 10°C/min is used at temperatures exceeding 700°C. When measuring the melting point of slag, a slag sample 3 mm in height and 2x2 mm in cross sectional area, was placed on an alumina sample holder in the furnace and heated up gradually in a nitrogen atmosphere. A magnified contour of the specimen is observed via the magnifier, as shown in Figure 10. Sketches of the samples are constantly drawn to show the changes in the shapes of the samples during heating. The temperatures of softening, active melting and flow point are registered. The definitions of these temperatures are as follows.

- **Softening**: The contour of the sample becomes smooth and no sharp border can be distinguished.
- **Active melting**: The melting is rapid and the shape of the specimen changes quickly.
- **Flow point**: The material flows out and the height of the specimen decreases to 1/3 of its original height.

![Figure 10 Contour of the sample at start of test (a), softening (b), active melting (c) flow point (d).](image)

As mentioned earlier, the tuyere slag in this study is considered to be formed by the ashes of coke and coal being burnt in front of tuyeres. When injection of flux is assumed, the composition of tuyere slag will also, necessarily, be altered by the injected flux. To make test specimens similar to the actual tuyere slag, the specimens were made of mixtures of coke and coal ashes, with or without additions of fluxes. The operational conditions of blast furnace No.2 at SSAB Tumplåt in Luleå, with a coal injection rate of 120-160 kg/thm and at the LKAB PBF, with a coal injection rate of ~110 kg/thm, are the basis for determining the correct mixtures of the specimens. The ratios of these materials used were different, depending on the different injection levels of coal and flux. Five levels of flux injection, no injection, low (L), medium (M), high (H) and very high (VH), were investigated in the tests. The amounts of different types of fluxes used varied, and were determined so as to achieve the same basicity of B2 (CaO/SiO2) in the tuyere slag for each injection level. The compositions of the specimens used are listed in Table 5.
2.1.2 Pilot-scale tests

The pilot-scale tests were performed in the LKAB PBF situated at Mefos in Luleå. It has a working volume of 8.2 m³ and a diameter of 1.2 m at tuyere level. From the tuyere level to stock line the height is 6 m. There are three tuyeres with a diameter of 54 mm placed at 120-degrees to each other. The raw material system consists of four bins for pellets or sinter, one bin for coke and two small bins for slag formers. Each material is weighed separately according to the actual recipe and put into a receiving hopper, located at the lower part of the skip bridge. The material is transported by a skip up to the furnace top and emptied into a receiving hopper. Below the receiving hopper there is a pressure equalising lock hopper. The top pressure can be regulated up to 1.5 bars of overpressure. In these tests the blast furnace was equipped with a bell with fixed armour and operated with a top pressure of 0.85 bar overpressure and coal injection of approximately 100 kg per tonne of hot metal. Burden probes were installed and material samples could be taken with horizontal probes at two levels in the shaft and by an inclined probe in the bosh [25].

Table 5. Composition of the specimens used for melting point measurements (wt%)

<table>
<thead>
<tr>
<th>No flux</th>
<th>BOF slag</th>
<th>Lime</th>
<th>Dolomite</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>CaO</td>
<td>2.02</td>
<td>12.09</td>
<td>18.03</td>
</tr>
<tr>
<td>MgO</td>
<td>1.28</td>
<td>4.29</td>
<td>6.07</td>
</tr>
<tr>
<td>SiO₂</td>
<td>51.90</td>
<td>41.07</td>
<td>34.67</td>
</tr>
<tr>
<td>MnO</td>
<td>0.01</td>
<td>1.00</td>
<td>1.59</td>
</tr>
<tr>
<td>FeO</td>
<td>4.23</td>
<td>6.72</td>
<td>9.53</td>
</tr>
<tr>
<td>Fe₂O₅</td>
<td>6.49</td>
<td>6.90</td>
<td>7.14</td>
</tr>
<tr>
<td>B₂</td>
<td>0.04</td>
<td>0.29</td>
<td>0.51</td>
</tr>
<tr>
<td>B₄</td>
<td>0.06</td>
<td>0.36</td>
<td>0.63</td>
</tr>
</tbody>
</table>

No, Low, High, Medium, Very high: represent the injection levels of flux
B₂=wt.%CaO/wt.%SiO₂; B₄= [(wt.%CaO+1.4wt.%MgO)/(wt.%SiO₂+0.59wt.%Al₂O₃)]

The charging of pellets, with an increased proportion of coarse pellets into the PBF was performed according to the experimental plan given in Table 6. Three different fractions, 9-12.5 mm, 12.5-16 mm and +16 mm, were obtained by screening MPBO normally charged into the blast furnaces at SSAB in Luleå. The experimental plan was adjusted during the test, because of difficulties in obtaining the correct screening analysis of the 12.5-16 mm fraction. The objectives were to verify that the process disturbances experienced at BF No.2 at SSAB were caused by the increased proportion of coarse pellets and also to find out whether the disturbances could only be caused by the increased proportion of the fraction +16 mm or both +16 mm and 12.5-16 mm fractions.

Table 6. Original and adjusted experimental plan for test in the PBF. The figures correspond to the % by weight of the 9-12.5 mm/12.5-16 mm/+16 mm fractions.

<table>
<thead>
<tr>
<th>Material</th>
<th>Planned particle size distribution</th>
<th>Real particle size distribution</th>
<th>Duration of test, hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference of MPBO</td>
<td>72/28/0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fraction No. 1</td>
<td>50/50/0</td>
<td>82/17/0</td>
<td>36</td>
</tr>
<tr>
<td>Fraction No. 2</td>
<td>40/40/20</td>
<td>66/22/12</td>
<td>21</td>
</tr>
<tr>
<td>Fraction No. 3</td>
<td>100/0/0</td>
<td>100/0/0</td>
<td>21</td>
</tr>
</tbody>
</table>

2.1.3 Full-scale tests

The full-scale tests were performed at the raw material handling unit supplying the No.2 blast furnace at SSAB Tunnplåt in Luleå. Production data from this blast furnace was also used. The raw material handling and the blast furnace have been rebuilt since the tests were performed. However, similar effects have been noticed on the new blast furnace No.3.
### Table 7. Chemical compositions of the test samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>CaO</th>
<th>SiO₂</th>
<th>MgO</th>
<th>Al₂O₃</th>
<th>Fe₂O₃</th>
<th>FeO</th>
<th>TFe</th>
<th>CaO/So₂</th>
<th>CaO+MgO/So₂</th>
<th>CaO+MgO/SiO₂+Al₂O₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pellet A</td>
<td>1.33</td>
<td>1.33</td>
<td>0.35</td>
<td>0.32</td>
<td>95.63</td>
<td>0.44</td>
<td>67.23</td>
<td>1.00</td>
<td>1.26</td>
<td>0.96</td>
</tr>
<tr>
<td>Pellet C</td>
<td>1.50</td>
<td>1.48</td>
<td>0.34</td>
<td>0.43</td>
<td>95.05</td>
<td>0.55</td>
<td>66.91</td>
<td>1.01</td>
<td>1.24</td>
<td>0.96</td>
</tr>
<tr>
<td>MPBO</td>
<td>0.28</td>
<td>1.97</td>
<td>1.48</td>
<td>0.36</td>
<td>94.54</td>
<td>0.77</td>
<td>66.72</td>
<td>0.14</td>
<td>0.89</td>
<td>0.75</td>
</tr>
<tr>
<td>KPBO</td>
<td>0.40</td>
<td>2.15</td>
<td>1.47</td>
<td>0.23</td>
<td>94.77</td>
<td>0.37</td>
<td>66.57</td>
<td>0.19</td>
<td>0.87</td>
<td>0.78</td>
</tr>
<tr>
<td>BOF slag</td>
<td>41.09</td>
<td>9.84</td>
<td>12.97</td>
<td>0.95</td>
<td>8.08</td>
<td>16.40</td>
<td>18.40</td>
<td>4.18</td>
<td>5.49</td>
<td>5.01</td>
</tr>
</tbody>
</table>

#### 2.1.4 Morphological studies

Studies using an optical microscope and by SEM have been performed on a number of samples from laboratory tests and the PBF. The chemical composition of the original materials, both those used for the softening and melting tests and those charged into the PBF, is shown in Table 7. Olivine pellets, fluxed pellets and BOF slag were studied in samples from softening and melting tests as well as excavation samples and probe samples from the PBF. On excavation, the pellet layers of the burden column were numbered starting with number one at the top of the blast furnace. The fluxed pellet and BOF slag were studied in samples from softening and melting tests and probe samples.
3. RESULTS AND DISCUSSION

3.1 Laboratory studies on melting properties of bosh slag and tuyere slag. (Paper 1)

The use of olivine pellets produced by the Swedish pellet supplier–LKAB in Malmberget and Kiruna–has considerably contributed to an improvement of the blast furnace performance at SSAB, Luleå Works Sweden [20]. To further develop the blast furnace performance, a new self-fluxed pellet was tested. The new pellet caused operational irregularities attributed to changes of melting properties of the pellet bed, when the basic fluxes were present. Ma theoretically analysed the test and proposed injection of fluxes through the tuyeres to avoid slag formation problems in the cohesive zone [2].

In order to determine the effect of fluxes on the melting characteristics of the self-fluxed pellets and the olivine pellets, softening and melting tests were carried out with two self-fluxed pellets and the two types of olivine pellets presently used at SSAB. Tests were carried out both with and without the addition of fluxes.

To find the effect of tuyere injection of fluxes on the properties of the tuyere slag, melting point measurements of tuyere slag specimens with and without addition of fluxes were carried out.

3.1.1 Softening and Melting Properties of Pellets

Table 8. Chemical composition of slag with pellet A

<table>
<thead>
<tr>
<th>Slag</th>
<th>Composition wt%</th>
<th>CaO/SiO2</th>
<th>(CaO+MgO) SiO2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CaO</td>
<td>SiO2</td>
<td>MgO</td>
</tr>
<tr>
<td>Primary</td>
<td>30.37</td>
<td>30.37</td>
<td>7.99</td>
</tr>
<tr>
<td>BOF</td>
<td>41.09</td>
<td>9.84</td>
<td>12.97</td>
</tr>
<tr>
<td>Bosh 1</td>
<td>43.92</td>
<td>23.51</td>
<td>12.96</td>
</tr>
<tr>
<td>Bosh 2</td>
<td>41.83</td>
<td>22.39</td>
<td>12.35</td>
</tr>
<tr>
<td>Bosh 3</td>
<td>39.67</td>
<td>21.23</td>
<td>11.71</td>
</tr>
<tr>
<td>Bosh 4</td>
<td>47.36</td>
<td>20.04</td>
<td>14.36</td>
</tr>
</tbody>
</table>

The two new types of self-fluxed pellets have lower softening and melting temperatures than the olivine pellets. However, the temperature intervals between the softening and melting of the self-fluxed pellets are slightly narrower than that of the olivine pellets tested. The test results also show that the softening and melting temperatures increase with the increase in the degree of pre-reduction.

According to its chemical composition as shown in Table 8, the primary slag, formed by the gangue content of pellet A, is located at a low melting temperature region in a ternary system of CaO-SiO2-MgO with 10% Al2O3, at point A shown in Figure 12(a). Its melting point is estimated to be about ~1300 °C. Since its basicity B2 is about 1, its viscosity is also supposed to be quite low. A good dripping property of the sample obtained could be one piece of evidence. Therefore, the pellet A itself ought not be the cause of slag formation problem.

3.1.2 Melting Property of BOF slag

Softening and melting tests of BOF slag were carried out in two types of crucibles, graphite and alumina. The results indicate that the melting property of BOF slag is strongly dependent on the presence of carbon. When BOF slag is sandwiched between two layers of coke in a graphite crucible, it does not melt down at all up to a temperature of 1500°C. On the contrary, when using an alumina crucible, the measured softening temperature of BOF slag is only about 1343°C, and it starts dripping at a temperature of 1400°C. The melting properties of BOF slag were changeable in the presence of carbon. Its melting point could be increased dramatically, but with very poor dripping. These phenomena can be considered a result of reduction of FeO in the slag by carbon. As
the basicity B2 of the BOF slag is about 4, a decrease in the FeO content would significantly increase its melting point. Chemical analysis of the BOF slag after the tests up to 1500°C showed that the FeO and Fe₂O₃ in the slag were only 5.3% and 1.5%, respectively, while the original ones were 16.4% and 8.08%, respectively. The melting temperature of the BOF-slag after the tests, according to our measurement result, was higher than 1520°C, which was much higher than that of the original BOF slag, about 1400°C.

3.1.3 Influence of Fluxes on the Melting Property of Pellets
The test results showed that the effects of fluxes on the softening and melting properties of pellets were different, depending on the type of pellets and of the fluxes used.

Influence of BOF slag on self-fluxed pellets
Generally, BOF slag could increase the melting temperature of the self-fluxed pellet considerably and the softening temperature slightly. The changes of the melting temperature were related to the distribution of BOF slag in the pellet bed. As shown in Figure 11, when BOF slag is evenly distributed in the pellet bed, the melting temperature increases dramatically by more than 80°C. No dripping material is collected at temperatures up to 1500°C. It seems that the BOF slag can block the dripping process entirely during the tests. Therefore, the melting point was not reached. When the BOF slag was unevenly distributed in the sample bed, the melting temperature increased by about 50°C, and the amount of the dripped metallic iron collected was decreased. When it was uniformly distributed under the pellet layer, no change of the melting temperature of the pellets could be seen. However, some white-grey powders could be found in the crucible after the tests for the latter two cases. A preliminary X-ray diffraction analyses showed that the white-grey powder contained di-calcium silicate (Ca₂SiO₄), and other complex compounds, e.g. 3CaO•Al₂O₃, 3CaO•SiO₂ etc. A TGA test showed that the melting temperature of the powder was higher than 1600°C, much higher than that of pellets and BOF slag. These results indicate that some compounds
with very high melting points, e.g. di-calcium silicate- (melting point ~2100°C), were formed during the test.

The addition of fluxes to a self-fluxed pellet bed causes a troublesome melting process. With dissolution of flux into the primary slag of self-fluxed pellets, the basicity of slag formed increases accordingly. If the inevitable segregation of top-charged flux is considered, the slag formed could have very high basicity locally. Table 8 lists some calculated compositions of slags, based on the samples used. Bosh slags 1-3 are three slags formed by the gangue content of pellet A with 5% BOF slag added, with no FeO content, 5% FeO content and about 10% FeO content, respectively. Bosh slag 4 is formed by the gangue content of pellet A and 10% BOF slag representing the case with segregation of BOF-slag. The basicities B2 of the bosh slags formed can reach up to 1.87 and 2.36, the same as or very close to the basicity B2 of di-calciumsilicate (2CaO·SiO₂, B2 = 1.87). As shown in Figure 12(a) both bosh slag 1 (A1) and 3 (A2) have much higher melting point than that of A. In addition, reduction of FeO can significantly change its melting point at this range of slag basicity. As shown in Figure 12(b) when basicity B2 is greater than 1, a decrease of FeO can increase the melting point considerably. Therefore, adding BOF slag to the samples will have a twofold effect on the melting properties: 1) It increases the melting point by an increased basicity; 2) It further increases the melting point by reduction of FeO in this region. In this case, a di-calciumsilicate with a very high melting point can be formed.

The influence of BOF slag on olivine pellets
As shown in Figure 13, in general, additional BOF slag decreases the melting temperature of samples for pellets with 75% and 90% pre-reduction, but has little effect on the softening temperature. The addition of 5% BOF slag to the pellet bed has more influence on the decrease of the melting temperature than the addition of 10% BOF slag. It has also been found that the flux has more influence on the melting temperature than on the softening temperature.

Both MPBO and KPBO pellets contain approximately 1.5% of MgO, but have a low basicity B2, quite different with that of self-fluxed pellets. Table 9 shows the chemical composition of some slags supposed to be formed during the melting process when using MPBO pellets. Bosh slags 1 and 2 represent the slags with the addition of 5% and 10% of BOF slag, respectively. The primary slag has an estimated melting point of about 1600°C, point M in Figure 12(a). When adding 5% or 10% of BOF slag, the basicity of the slags formed increases as shown in Table 9. Accordingly, the melting point of slag decreased to be about 1350°C and 1550°C, as points M1 and M2 of Figure 12(b). Therefore, the addition of 5% BOF-slag can considerably improve the melting property. However, adding 10% has less effect. A further increase in CaO content may increase its melting point dramatically, due to the increase of the slag basicity.

<table>
<thead>
<tr>
<th>Slag</th>
<th>Composition, wt%</th>
<th>CaO</th>
<th>MgO</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>FeO</th>
<th>TiO₂</th>
<th>CaO/SiO₂</th>
<th>(CaO+MgO)/SiO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td></td>
<td>5.01</td>
<td>28.52</td>
<td>37.38</td>
<td>8.29</td>
<td>15.41</td>
<td>5.39</td>
<td>0.13</td>
<td>0.89</td>
</tr>
<tr>
<td>BOF</td>
<td></td>
<td>41.09</td>
<td>9.84</td>
<td>12.97</td>
<td>0.95</td>
<td>16.40</td>
<td>1.89</td>
<td>4.18</td>
<td>5.49</td>
</tr>
<tr>
<td>Bosh slag 1</td>
<td></td>
<td>27.13</td>
<td>26.49</td>
<td>34.76</td>
<td>6.61</td>
<td>0</td>
<td>5.03</td>
<td>0.78</td>
<td>1.54</td>
</tr>
<tr>
<td>Bosh slag 2</td>
<td></td>
<td>36.63</td>
<td>23.25</td>
<td>30.53</td>
<td>5.18</td>
<td>0</td>
<td>4.42</td>
<td>1.20</td>
<td>1.96</td>
</tr>
</tbody>
</table>

Figure 13. Variation of the Softening and melting temperatures of MPBO and KPBO with the addition of BOF slag (Degree of pre-reduction of pellets = 75%).
Influences of some other basic additions
Tests adding limestone or burnt dolomite to a sample bed of pellet A were also conducted. The basicity B2—CaO/SiO₂ or B3—(CaO+MgO)/SiO₂ of the samples was adjusted to be the same as that of adding 5% BOF slag. The pellets used were pre-reduced to a degree of 75%. Slag formers were evenly distributed in the pellet bed. The results showed that limestone or burnt dolomite could increase the melting temperature of pellet A by about 30°C and 25°C, respectively, much less than the influence of BOF slag.

3.1.4 Effect of Fluxes on Melting Points of Coke and Coal Ashes
The addition of fluxes to coke and coal ashes, corresponding to the tuyere slag with injection of flux, can considerably lower the melting temperature and the interval between the softening and melting temperatures. The effect on melting temperature of coal and coke ashes by the addition of fluxes is shown in Figure 14. The changes of the melting temperature varied with the types and the amounts of the fluxes used.

![Figure 14. Melting temperature of specimens with changes of flux added.](image)

Generally, the melting temperature of the specimens decreases significantly with the increase of the addition of BOF slag or lime, up to the “high” level. Further increasing the addition of BOF slag and lime to the “very high” level will increase the melting point of the specimen slightly. By adding dolomite to a “low” injection level its melting point will be considerably decreased. However, a further increase of the additions will increase its melting point, as shown in Figure 14.

Addition of fluxes to coke and coal ashes enhances the melting process. The coke and coal ashes mainly contain the acid components Al₂O₃ and SiO₂. Their melting points are generally high, combined with a very high viscosity. For instance, the melting point of a specimen, corresponding to a tuyere slag formed by a mixture of coke and coal ashes, was about 1600°C. When adding flux to the specimen, the acid components were neutralised. The basicity of the slags formed was increased with an increased addition of fluxes. When using a “high” or a “very high” level of addition, the basicity B2 was around 1.0, quite close to a normal final slag in the blast furnace. Its estimated melting point is only about 1300°C, much lower than the original one. In addition, we can expect that its viscosity would also be quite low.

Compared to lime and dolomite the BOF slag has a different effect on the lowering of the melting point of the coke and coal ashes. This may be due mainly to the differences in the MgO and Al₂O₃ content of the specimens and contents of some other oxides, such as iron oxides and manganese oxides, in the specimens containing BOF slag.

3.1.5 Influence of Fluxes on Slag Formation Process
The slag formation in the blast furnace is a complex process, involving the softening and melting of burden, dissolution of slag formers and additives in the primary slag, absorption of ashes of fuels by bosh slag, and various chemical reactions, etc.

The major objective of using fluxes in the blast furnace process is to neutralise the gangue of iron ores and ashes of reductants. However, most of the ash of the reductants is released at this point in time, when fuels are burnt in front of tuyeres. Therefore, the bosh slag has a higher basicity than that of the primary and final slags. When the basicity of bosh slag is high, considerable changes of the slag properties during the transformations from primary slag to bosh slag and from bosh slag to
final slag occur. Obviously, the influence of fluxes on the slag formation process is dependent on the ferrous burden used and the way in which fluxes are delivered into the blast furnace process.

When acid pellets are used, the top-charged fluxes neutralised the acid components in the burden, generally improving its melting properties until reaching a certain limit. Above this limit the slag properties may still become worse. On the other hand, when self-fluxed pellets are used, the top-charged fluxes generally gave the bosh slag an excessive basicity, which had quite a negative effect on the melting properties. In order to avoid an excessive basic slag formed at the cohesive zone and a very acid slag formed in front of tuyeres, injection of a certain amount of fluxes into the blast furnace can be a good solution.

3.2 Morphological studies on samples from laboratory tests and PBF (Paper 2)

Based on the proposal for tuyere injection of fluxes into the blast furnace morphological studies have been made of samples from previous softening and melting tests as well as probe samples and samples from excavation of LKAB PBF at Mefos.

3.2.1 Slag formation when using fluxed pellets and BOF slag

Samples from softening and melting tests were studied by SEM analyses. Figure 15 shows a macroscopic drawing of the residual material after completing the softening and melting test on a sample consisting of pellet A and BOF slag. The maximum temperature reached in the test was about 1550°C. The images found in Figures 16-18 correspond to the marked areas in the drawing. The iron oxide in the pellet is reduced to metallic iron found at the top of the crucible after the test. Below, there are residuals of BOF slag and further down a second slag of another chemical composition. At the bottom, mixed with the coke, a third slag is found. Figure 16 shows an image from the border of pellet A and BOF slag.

Figure 15. Cross section of sample after softening and melting tests. The marked areas indicate from bottom to top the material corresponding to the images in Figure 16, Figure 17 and Figure 18.

Figure 16. Sample from a test with pellet A and BOF slag.

Figure 17. Slag phase in the intermediate region.

Figure 18. Slag found in the coke layer.
residuals of BOF slag. The SEM images of the second and third slag phases are shown in Figure 17 and Figure 18, respectively. The metallic iron is entrained by the slag phases and the dripping is stopped. In the residuals of BOF slag two phases mainly consisting of (Ca, Si, Al)O and (Fe, Mg, Mn)O are widely spread. The chemical composition of these phases varies, e.g. (Ca, Si, Al)O, which is found also in the border of metal and BOF slag, is dominated by either Si or Al. The intensity of Al is high compared to that of BOF slag in the other samples studied. Metallic Fe and V are found in the BOF slag. The slag in the intermediate region seen in Figure 17 mainly contains (Ca, Si)O and small grains of MgO. The newly formed slag phase, found among the coke, shown in Figure 18 mainly consists of (Ca, Si,O, with a very high amount of Ca. No FeO is detected either in the intermediate slag or in the slag at the bottom. A few metallic grains of Fe are found in the intermediate slag. Larger areas of Fe met are detected in the slag at the bottom. Point analyses made in SEM and XRD analyses indicate the presence of di-calciumsilicates and tri-calciumsilicates. Concerning this matter further analysis must be made.

The results from the study of the softening and melting sample containing fluxed pellets and BOF slag give an idea about what happened in the test. With the self-fluxed pellets an early melting primary slag (~1300°C) can start dripping. The results from the study of the sample from a softening and melting test show that the composition of the BOF slag has changed and that slags quite different from BOF slag are formed during the test. One of these new slags is found re-solidified at the bottom of the crucible. All three slags studied—the residual BOF slag, the intermediate slag and the new slag—could have stopped the metal from flowing down and dripping out of the crucible. The slag found at the bottom of the crucible mainly consisted of (Ca, Si)O of a high Ca content and with a lower content of Mg and Al and no FeO. The known facts indicate the course of softening and melting test to be as follows. The pellets are reduced to Fe met and the primary slag containing some FeO melts and starts to drip down. The BOF slag partly dissolves into the liquid slag and its basicity gradually increases. The FeO in the liquid slag is reduced to Fe met. As a result, the melting point of this new slag increases more than can be compensated for by the increase of temperature during the test and the viscosity also increases. When the metallic iron finally melts and is supposed to drip down, it is entrained by both the residual BOF slag pieces that have partly melted and adhered to each other as well as by the high viscosity slag at the bottom of the crucible. The XRD analysis made on the newly formed slag at the bottom of the crucible indicated that it consists of di-calciumsilicate and tri-calcium silicate. From the analyses made some approximate estimations of melting temperature can be derived based on the assumption that the slag of Pellet A mainly dissolves more CaO when interacting with the BOF slag. As can be seen in Figure 19, the melting point of the newly formed slag (S) is much higher as compared to the primary slag (A) of the pellet (~1300°C).
3.2.2 Slag formation when using olivine pellets and BOF slag

The zone of close contact between MPBO and BOF slag in a sample from a softening and melting test interrupted at about 1400°C can be seen in Figure 20. The pellet is quite well reduced and the metal has melted together. The BOF slag consists of a matrix of (Ca,Si)O with Ca as the main component. The Si is sometimes partly exchanged for V or more seldom for Al. Ca sometimes occurs as CaO and some areas containing (Ca,Si,Fe,V)O are also found. The Si content in the BOF slag is higher close to the pellet border. B2 of the main phase that varies in the range 1.5-5.5 with an average of 2.4 in the BOF slag has decreased to 1.9 on average close to the BOF slag/pellet border. The concentration of Ca in the pellet, close to the pellet/BOF slag border, increases. As can be seen in Figure 20, B2 of the pellet slag phase has increased to about 1.6-2.0 at the pellet/BOF slag border as compared to the maximum value of about 0.6 found when the pellet is not in contact with the BOF slag. A high concentration of Mg, combined with Fe and sometimes also Mn, is found in the BOF slag close to the border indicating (Fe,Mg,)O and (Fe, Mg, Mn)O. Further inside the BOF slag (Fe,Mg,Mn)O there is much less Fe, but Fe_{met} is present.

Excavation samples of pellets and BOF slag from layers 21 and 23 were prepared for SEM studies. Layer 21 is found just above the cohesive zone and layer 23 is part of the cohesive zone. Some images obtained from the SEM analyses are shown in Figure 21 and Figure 22. The pellets of layer 21 have a structure consisting of metallic iron with quite high porosity [21]. The pellets are highly reduced and, as a consequence of a low gangue content only small areas of slag are found. Pellet and BOF slag stick to each other. The BOF slag structure is quite similar to the original one and no sign of melting can be seen. This sample of BOF slag starts to soften at about 1255°C and flows out at 1334°C. The phase of the BOF slag containing (Ca,Si)O (A in Figure 21) extends over large areas. In this phase, Si is partly exchanged for V, more seldom for Al. Some areas of this phase have a higher intensity of Ca in the form of CaO or (Ca,Fe)O. Another phase of the BOF slag, seen as distinct spherical grains (B in Figure 21), consists of...
The border between the pellet and the BOF slag is clear, but the SEM analyses indicate a slight increase of Ca at the pellet surface in contact with the BOF slag.

As expected, the shells of the pellets of layer 23 are also well reduced, but the porosity of the shells is much lower compared to that of the previous sample. The BOF slag is deformed and the melting has probably just started. Its softening temperature and flow point were recorded as 1288°C and 1344°C respectively. The main phase in the BOF slag seems different, but the composition is still about the same as in the BOF slag of layer 21. No areas with a high intensity of Ca for free lime are detected and the distinct spherical grains of mainly (Fe,Mg)O have lost their shape and floated out. However, the overall chemical composition based on chemical analyses shows an increased content of SiO₂, MgO and Al₂O₃ in the BOF slag of layer 23 compared to that of layer 21. In the pellets, close to the BOF slag border, higher amounts especially of Ca, but also of Mg are found. In the slag phase of the pellets Ca and Mg exist in combination with Si and sometimes also with Al. The increased content of Ca and Mg extends about 0.5 mm into the pellet.

The SEM studies of softening and melting samples, and of samples from the PBF, show that olivine pellets and BOF slag interact during start of softening and melting only if the pellet and the BOF slag are in contact with each other. If the pellet is not in contact with the BOF slag only the components of the blast furnace gas will interact with the pellet. It means that the slag formation for different pellets in the burden will be quite different depending on whether they are close to another pellets, a basic flux or an acid flux. The basicity of the slag formed at different positions in the burden can vary quite a lot in chemical composition as well as in basicity. Therefore, even slag properties such as melting temperature and viscosity will vary. The variation is even higher when an uneven distribution of fluxes is considered. By injection of slag formers these variations will decrease.

The SEM studies of softening and melting samples and of samples from the PBF show no interaction between BOF slag and the olivine pellets before softening and melting has started. This also explains why the main effect of BOF slag was found regarding the melting temperature [4], and not the softening temperature, when BOF slag was added to the pellet bed in a softening and melting test. A sample consisting of equal parts of BOF slag and pellet shell from layer 21 starts to melt before 1300°C. The interaction between BOF slag and olivine pellets can probably start at about that temperature. At first, an effect of interaction can be seen only on the surface of the pellets and BOF slag, mainly as an increased amount of Ca and Si. When the temperature is further increased higher amounts of both Ca and Mg are found in the pellet. The high basicity of BOF slag includes an excess of Ca and free CaO is found in a matrix consisting mainly of Ca and Si, but also some V and Al. This free CaO seems to move more easily and can therefore interact with the other burden materials. Mg is quite strongly bonded in the (Fe,Mg)O and (Fe,Mg,Mn)O, until Fe²⁺ is reduced to Fe₅net and the BOF slag starts to melt. In layer 23 an effect on the overall chemical composition of the BOF slag can be seen and not only at the BOF slag surface. The BOF slag is deformed and has almost melted which means that the diffusion of ions increases. The core part of the pellet that sometimes melts and entrains out of the pellet can also interact with this almost melted BOF slag. The entrained slag probably includes SiO₂ and FeO as the content of these in the residuals of the core decreases, while the MgO content increases. The melting point of the residual material in the core is very high.

The changes of chemical composition of individual pellets will strongly depend on the environment. Nevertheless, there is a slight increase in the Ca content and a decrease in the Si content in the slag phase of MPBO in all samples and as a result the basicity is increased.

Earlier studies showed that the melting properties of BOF slag could vary. Different processes having influence on the melting point of BOF slag occur. 1) Reduction of FeO from (Fe,Mg)O and
Flow of Ca and Si out of and into BOF slag. 3) Direct reduction of manganese from \((\text{Mg},\text{Mn})_0\). An increased FeO content of BOF slag at the first step of reduction might explain the decrease in the melting temperature from layer 9 to layer 14 and further to layer 21. The reduction rate increases at higher temperatures and in layer 23 the degree of reduction of the BOF slag is estimated to be approximately 80%. At the same time the basicity decreases. This combined effect and the fact that the manganese is still part of the slag phase might explain that the increase in the melting temperature is limited. It is probable that in a pellet burden consisting of olivine pellets the BOF slag will dissolve the gangue of the olivine pellet at the same time as the reduction rate increases. Therefore, the melting point will not be increased and the slag formation process is not disturbed when top-charging fluxes together with olivine pellets. On the other hand this will be the case with the self-fluxed pellets.

3.3 Study on the effect of pellet size on blast furnace process in laboratory, pilot scale and full-scale tests. (Paper 3)

Low filling levels in pellet silos and pellet bins have caused several severe disturbances of the blast furnace process over the years. These disturbances included low gas utilisation, large variations in permeability of burden column, large variations of heat load, low hot metal temperature, low chemical energy of hot metal and series of slips. The traditional explanation for the disturbances has been the increased amount of fines entering the blast furnace at low filling levels of pellet bins. By emptying pellet bins on two different occasions, it was found, contrary expectation, that the amount of coarse pellet charged into the blast furnace increased when the filling level was decreased to approximately 40%. To verify that the disturbances in the blast furnace process were caused by the coarse fraction of pellets, tests with monitored charging of different pellet fractions were carried out at the LKAB PBF at MEFOS. The experiments confirmed that a high ratio of pellets +12.5 mm caused the production disturbances. The effect was also studied in laboratory tests—reduction and softening and melting tests—on different size fractions of pellets to determine why the coarser fractions cause these process disturbances. An evaluation of the laboratory tests as well as the data from the tests in the PBF has been made.

3.3.1 Pilot scale test – charging of increased ratios of oversized pellets into the PBF.
The results from the pilot scale tests are stated in Table 10. The gas utilisation in the first period of testing, when pellets of the reference fraction are charged, varies as a result of some process disturbances, including a chilled hearth that was remedied just before the start of the test. The blast furnace performance deteriorates gradually, when the particle size distribution of charged pellets includes increased proportions of pellets of 12.5-16 mm and +16 mm fractions. The gas utilisation decreases and starts to vary more, when pellets of particle size distribution 66/22/12 are charged. The burden descent also becomes irregular and sometimes decreases to 2 cm/min, as compared to normal values of 4-5 cm/min for MPBO. Some small slips occur at the same time as EtaCO (gas utilisation) reaches minimum values of approximately 44. After the start of charging pellets of particle size distribution 33/37/30, the gas utilisation decreases further and starts to vary even more.

Table 10. Average of process data related to particle size distribution of charged pellets. Data is based on data per hour except for EtaCO which is based on data per minute.

<table>
<thead>
<tr>
<th>Particle size distribution 9-12.5/12.5-16/+16</th>
<th>EtaCO Average</th>
<th>EtaCO Std. deviation</th>
<th>Sol. Loss, Kg/thm Average</th>
<th>Sol. Loss, Std. deviation</th>
<th>pV bosh, Average</th>
<th>pV bosh, Std. deviation</th>
<th>Burden descendent cm/min</th>
<th>Burden descendent Std. deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>72/28/0</td>
<td>49</td>
<td>1.4</td>
<td>95</td>
<td>2.2</td>
<td>5.8</td>
<td>0.19</td>
<td>4.8</td>
<td>0.6</td>
</tr>
<tr>
<td>82/17/0</td>
<td>49</td>
<td>1.2</td>
<td>91</td>
<td>16</td>
<td>5.2</td>
<td>0.96</td>
<td>4.5</td>
<td>0.5</td>
</tr>
<tr>
<td>66/22/12</td>
<td>48</td>
<td>1.3</td>
<td>99</td>
<td>4.1</td>
<td>5.4</td>
<td>0.44</td>
<td>4.0</td>
<td>0.6</td>
</tr>
<tr>
<td>33/37/30</td>
<td>47</td>
<td>1.6</td>
<td>100</td>
<td>4.8</td>
<td>5.0</td>
<td>0.55</td>
<td>4.2</td>
<td>0.5</td>
</tr>
<tr>
<td>100/0/0</td>
<td>50</td>
<td>1.3</td>
<td>95</td>
<td>2.8</td>
<td>5.4</td>
<td>0.21</td>
<td>4.3</td>
<td>0.3</td>
</tr>
</tbody>
</table>


The lowest value of EtaCO is 41.8 during this period. When charging the pellets of particle size distribution 33/37/30 a couple of small slips occurred, as well as some periods with quite long intervals between the dumps. The blast furnace performance improves rapidly, when pellets of particle size distribution 100/0/0 are charged into the PBF. The gas utilisation increases to an average of 50%.

During the test period samples are taken with a shaft probe in the upper part of the shaft and with an inclined probe just above the cohesive zone. The samples are studied in an optical microscope and in a SEM. The samples from the upper shaft have very low degrees of reduction and are composed mainly of magnetite and hematite. A difference between the core and the shell is noticeable, especially for the samples containing larger pellets, which also contain more cracks than the smaller pellets. The samples taken with the inclined probe, one of which is shown in Figure 24, are highly reduced and sharp borders between the cores and the shells can be seen with the naked eye. At this border between the metallic shell and the core, where there is a high content of wustite, a sintered band of metallic iron is also found. The shell thickness is independent of pellet size and therefore the size of the core decreases with decreased pellet size. The core, especially in the larger pellets, seemed to be pushing its way out from the pellets and through the shell. Studies in a microscope and SEM show that the amount of metallic iron in the centre of the core is much higher in the smaller pellets than in the larger ones. This can be seen in Figure 23. MgO is dissolved in the iron oxide at low reduction degrees. At high degrees of reduction, as in the shell part, MgO is found in the slag. The MgO content of the slag observed in the core between the iron oxide grains is less than 1% and the FeO content is ~20%. The MgO content of the slag of approximately the same FeO content seems to increase when moving from the centre of the pellets towards the outer parts. The Fe content of the slag is high at low degrees of reduction, and decreases when the reduction degree increases. The MgO content observed in the wustite in the core of the coarse pellets is ~1.5%, compared to ~3-4% in the normal sized pellets.

3.3.2 Laboratory tests

3.3.2.1 Properties of oxidised pellets

The results from tumbler strength test according to ISO 3271 and the porosity measurements in mercury can be found in Table 11. Both the tumbler strength and the porosity are about the same for the 9-12.5 mm and 12.5-16 mm fractions, but lower values were measured in the +16 mm fraction. The distribution of pore size changes towards finer pores when the pellet size increases.
Study of the pellets in the optical microscope reveals that all pellet fractions are similar with respect to both core and shell structure. The cores are generally characterised by a high degree of sintering, but a low degree of oxidation, while the shells are characterised by a high degree of oxidation, but a low degree of sintering. The thickness of the shell is independent of pellet size; therefore the core increases with increased pellet diameter. Depending on the degree of oxidation, more or less residual magnetite is found. In these samples the amount of residual magnetite is higher in the pellets of +16mm fraction compared to the 12.5-16 mm and 9-12.5 mm fractions. The amount of residual magnetite can vary in the same fraction of pellets, too. Pellets of the 9-12.5 mm fraction are almost fully oxidised. This is expected, as the oxidation starts at the pellet surface and proceeds topochemically. Thus, the time needed to complete the oxidation of the pellets depends on pellet size. In the centre of a large pellet the hematite often exists in limited areas, often in the form of lamellas. Grains of olivine that have partly reacted can be found throughout the pellet. Close to these grains magnesia ferrite can be observed.

### Table 11. The tumbler strength and the total porosity of pellets of different fractions.

<table>
<thead>
<tr>
<th>Fraction of pellets, mm</th>
<th>Tumbler strength, %</th>
<th>Total porosity, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>9-12.5</td>
<td>96.3</td>
<td>25.5</td>
</tr>
<tr>
<td>12.5-16</td>
<td>96.6</td>
<td>25.1</td>
</tr>
<tr>
<td>+16</td>
<td>95.0</td>
<td>22.8</td>
</tr>
</tbody>
</table>

### Table 12. Summarised results from blast furnace simulated reduction.

<table>
<thead>
<tr>
<th>Fraction mm</th>
<th>Reduction degree, after 60 min, %</th>
<th>R₄₀, %/min</th>
<th>Change of Pressure drop, mm H₂O</th>
<th>Bed shrinkage, %</th>
<th>Final reduction degree, %</th>
<th>Reduction time, min</th>
</tr>
</thead>
<tbody>
<tr>
<td>9-12.5</td>
<td>20</td>
<td>0.5</td>
<td>3.15</td>
<td>15.3</td>
<td>80.1</td>
<td>207</td>
</tr>
<tr>
<td>12.5-16</td>
<td>19</td>
<td>0.5</td>
<td>3.05</td>
<td>13.5</td>
<td>80.2</td>
<td>215</td>
</tr>
<tr>
<td>+16</td>
<td>18</td>
<td>0.4</td>
<td>2.95</td>
<td>12.6</td>
<td>77.6</td>
<td>220</td>
</tr>
</tbody>
</table>

### Reduction rate

Reduction properties of the pellets have been tested according to two different test procedures; one of them simulating the upper part of the shaft, where the pellets are reduced to a 30% degree of reduction; and one according to a blast furnace simulating test routine, where the pellets are reduced to a 65% and an 80% degree of reduction, respectively. The pellets pre-reduced to a 30% degree of reduction were tested in softening and melting tests in the blast furnace simulation model at MEFOS. The pellets pre-reduced to reduction degrees of 65% and 80%, respectively, were studied in the microscope, tested by tumbling and in softening and melting tests at the metallurgical laboratory (CK-lab) of LKAB, Malmberget.

When the pellets are pre-reduced to wustite they are pre-heated to 400°C before a reduction gas consisting of 60%N₂/20%CO₂/15%CO/6%H₂ is introduced. The time needed to achieve a 30% reduction degree increases when the particle size of the pellets increases.
A blast-furnace-simulated reduction test was made to simulate the final degrees of reduction of 65% and 80%. The changes in composition of reducing gas and degree of reduction of the pellets can be seen in Figure 25. The pellets of the 9-12.5 mm fraction first reach a ~30% degree of reduction. At this point in the test the reducing gas is too weak to reduce the material further. Therefore, the two fractions containing larger pellets are allowed to catch up with the fraction of 9-12.5 mm. The differences in reduction rate will therefore be less than maximum, but the result might still be representative of the blast furnace conditions. As can be seen in Table 12 the degrees of reduction after 60 min are 20%, 19% and 18% for the 9-12.5 mm, 12.5-16 mm and +16 mm fractions respectively. R40—the reduction rate at a 40% degree of reduction of the pellets—is only slightly lower for the +16 mm fraction. Partly as a result of crack formation both the decrease in bed height and the pressure drop over the pellet bed are lowest for the +16 mm fraction and highest for the 9-12.5 mm fraction.

**Effect of reduction on disintegration and structure**

During the reduction of the 65% and 80% degrees of reduction the pellets disintegrate and the disintegration increases with increasing particle size of pellets. As can be seen from the photographs of the samples reduced to a 65% degree of reduction in Figure 26, the cracking of the pellets increases, when the particle size of the pellets increases. The disintegration of both the oxidised and reduced pellets is also measured by a tumbling test. The results, which can be seen in Figure 27, show that although the tumbling strength and abrasion are approximately the same for all fractions before reduction, they will decrease and increase more, respectively, when the pellet size increases. This means that the larger pellets more easily generate fines both by cracking and abrasion. After tumbling a lot of naked cores, from which the shells have fallen off, are found in the samples of pellets of 12.5-16 mm and +16 mm fractions.

Reduction of the pellets is also carried out in a swelling test, where eighteen pellets were reduced to an 80% degree of reduction at 1000°C in a reducing gas consisting of 60%N₂/40%C₀. The swelling is estimated from volume measurement in mercury and average diameter is measured by measuring the total length of the row of pellets with an inclined ruler. As can be seen in Figure 28, the swelling increases, when the particle size of pellets increases. The lower swelling estimated by volume measurements in mercury is explained by the formation of large cracks that are filled with mercury during volume measurement.

![Figure 26. Photos of samples of pellets after reduction to a 65% reduction degree.](image)

![Figure 27. Disintegration and abrasion of oxidised and reduced pellets.](image)
The different fractions of pellets reduced to a 65% degree of reduction were studied by chemical analyses and using an optical microscope. As expected the chemical analyses of the material from the cores and the shells of the different fractions indicate a much higher FeO content and a lower Fe\text{met} content in the cores compared to those of the shells. A comparison of the content of Fe\text{met} and FeO in cores and shells of different fractions can be seen in Figure 29. The shells are well reduced and the shells of pellets of larger diameter contain even more Fe\text{met} compared to the pellets of a 9-12.5 mm fraction. This can be explained by the fact that the reduction time increases with increased pellet diameter. Studies using the optical microscope indicate the same with respect to the degree of reduction in both the shell and core. The results from the morphological studies of laboratory-reduced pellets of different sizes are similar to the results from studies of samples from PBF. The shell is of about the same thickness and independent of the pellet diameter. The diameter of the core increases with increased pellet diameter. The shells are generally well reduced, but the amount of Fe\text{met} decreases slightly when comparing the outer part of the shell with the inner part of it. The amount of Fe\text{met} decreases towards the centre of the pellets. In the largest pellets almost no metallic iron is found in the centre.

Softening and melting behaviour
The softening and melting properties of pellets pre-reduced to a 30% degree of reduction were evaluated under blast-furnace-simulated conditions using the MEFOS blast furnace model [26]. The samples of a total weight of ~ 640 g consisted of pellets pre-reduced to a reduction degree of approximately 30% and 7% BOF slag evenly distributed in the pellet bed. BOF slag was added to get approximately the same basicity as in the blast furnace burden. The sample was sandwiched between coke layers in a graphite crucible with a diameter of 80 mm. A load of 49 kPa was applied and a total gas flow of 270 l/min was introduced. The gas consisted of 100% N\textsubscript{2} up to 900°C and after that of 61% N\textsubscript{2}, 35% CO and 4% H\textsubscript{2}. Several types of data are logged during the test; such as temperature, shrinkage of bed and the pressure drop over the bed. Both full tests up to dripping, at the point when the bed stops shrinking, and tests interrupted at approximately 1450°C, just before pressure drop starts to increase rapidly and the melting starts, were performed. The softening temperature is defined as the temperature at which the shrinkage of the bed is 50% (T\textsubscript{50%}). The melt out temperature is defined as the temperature at which the maximum pressure drop is registered (T\text{Pmax}). The width of the cohesive zone is defined as the interval from the start of the softening process until the bed stops shrinking (T\text{(end of shrinkage)} - T\text{50%}). As can be seen in Table 13, the melt out temperature, as well as the width of the cohesive zone increases with increased pellet diameter. The width of the cohesive

| Table 13. Temperatures of softening and melting of the pellet bed, all data in °C |
|---------------------------------|-----------------|-----------------|-----------------|
|                                | 9-12.5 | 12.5-16 | +16 |
| T\textsubscript{50%}           | 1434   | 1432   | 1411 |
| T\text{Pmax}                  | 1464   | 1490   | 1506 |
| T\text{(end of shrinkage)}    | 1506   | 1525   | 1531 |
| Cohesive zone                 | 72     | 93     | 120  |

| Table 14. Chemical composition of dripping metal |
|-----------------------------------------------|-------|-------|-------|-------|
|                                | C, %  | Si, % | Mn, % | O, ppm |
| 9-12.5                          | 4.92  | 0.46  | 0.10  | 33     |
| 12.5-16                         | 4.67  | 0.31  | 0.12  | 31     |
| +16                             | 2.48  | 0.21  | 0.07  | 330    |
zone is increased as a result of a decreased softening temperature, an increased melt out temperature and an increased temperature at the stop of bed shrinkage. The pressure drop around 1300°C increased with the increased pellet diameter, but the pressure drop at melt down decreased with the increased pellet diameter. The chemical composition of the dripping metal is to be found in Table 14. The chemical energy—the amount of C, Si and Mn dissolved in the dripped metal—of the dripped metal decreases, when the pellet diameter increases.

Studies of quenched samples of 9-12.5 mm and +16 mm fractions from interrupted tests carried out under an optical microscope and by SEM indicated higher amounts of residual oxygen and considerably higher amounts of slag containing iron oxide in the sample of the +16 mm fraction compared to those in the sample of the 9-12.5 mm fraction. One image from each fraction showing, the difference in slag content, is to be found in Figure 30.

Softening and melting tests in an N₂ atmosphere were performed on pellets of the three fractions pre-reduced to degrees of reduction of 65% and 80%. Also in these tests, 7% BOF slag was added to the bed and the sample is sandwiched between coke layers in a graphite crucible measuring 40 mm in diameter. The tests show that the softening and melting temperatures increase with increased reduction degree. The softening and melting temperatures are comparable for the 9-12.5 mm and 12.5-16 mm fractions, but lower for the +16 mm fraction. The dripping starts approximately 35°C earlier for the +16 mm fraction as compared to the 9-12.5 mm and 12.5-16 mm fractions for both the 65% and 80% degrees of reduction. No significant difference related to the fractions is found for the temperatures when shrinkage stops or stop of dripping stops.

![Figure 30. Image from the centres of pellets of 9-12.5 mm and +16 mm fractions. A=metallic iron, C=slag](image)

### 3.3.3 Discussion of results
#### Structure of the pellets
There is a heterogeneity of structure in the pellets—meaning that the structure of the core differs from that of the shell—for both oxidised and reduced pellets. The same pellet structure is found in all fractions, but the volume of the core structure increases with increased pellet diameter. For the oxidised pellets, the amount of residual magnetite in the centre increases with increased pellet diameter. In the reduced pellets the amount of wustite is much higher in the centre as compared to the shell. The heterogeneity of structure is similar for pellets reduced to both 65% and 80% degrees of reduction but even more pronounced for the latter. The amount of metallic iron in the centre of the reduced pellet decreases, while the FeO content increases with increased pellet diameter.

#### Permeability
When charging higher ratios of the +16 mm and 12.5-16 mm fractions increased variations in permeability over the blast furnace have often been experienced. An increase in permeability can be seen at the start of charging of increased proportions of oversized pellets, and periods of high and
low permeability recur during the periods when a high portion of coarse pellets is charged into the blast furnace. Together with the variations in permeability, decreased and more varied gas efficiency and greatly varied burden movements also occur. The phenomena affecting the permeability of the blast furnace burden also changes the gas distribution in the blast furnace. When operating with high rates of coal injection the amount of coke is greatly decreased. The phenomena changing the permeability will therefore have great impact on the blast furnace process. When operating the blast furnace with a greater amount of coke and less coal injection the coke layers will stabilise the gas distribution to a greater extent and the effect of the coarse pellets on the blast furnace process will be limited.

**The effect of disintegration**—The disintegration of pellets during reduction increases with increased pellet diameter. On tumbling after reduction disintegration increases with increased pellet diameter. Further the swelling tests show increased crack formation and swelling with increased particle size. This means that even if the original reason for disturbance in the blast furnace process was not the charging of pellet fines into the blast furnace at low filling levels of pellet bins, the process disturbance might still be caused by secondarily formed fines. The process disturbances in the blast furnace might be partly due to the formation of large amount of fines inside the blast furnace as a result of disintegration of the oversized pellets during reduction. The typical symptoms of fines in the blast furnace are irregular burden descent and variations in gas utilisation, caused by inactive zones in the blast furnace, which disturb the gas distribution.

**The effect of softening and melting properties**—The three pellet fractions studied differ in softening and melting performance. On softening, the bed shrinkage and pressure drop increases with an increased pellet size. The temperature interval of the estimated cohesive zone increases with increased pellet size. This may partly explain the periods of increased pressure drop, when the blast furnace is charged with increased ratios of coarse pellets.

The pellets taken from the PBF with the inclined probe contains wustite with some MgO. Both core size and FeO content increase with increased pellet size. The MgO in the wustite will increase the melting point of the wustite phase [1][22], but the MgO content of the wustite phase is much lower in the coarse pellets than in those of normal size. When magnesiowustite is further reduced the MgO is dissolved in the slag phase and increases the liquidus temperature of the slag, which initially contains considerable amounts of FeO [1][22]. In the cores of all the pellets studied the slag contains less than 1% MgO but up to ~4% CaO. The melting point of this slag low in MgO content, varies depending on the chemical composition, and especially on the FeO content, as in the area shown in the phase-diagram in **Figure 31**. The area drawn is based on normalised values of the main chemical components of the slag phase. High amounts of wustite with low concentrations of MgO as well as high amounts of early melting slag may cause a lower softening temperature and therefore larger deformation of the pellets. The core can also more easily entrain out through the pellet shell if the amount of liquid material formed is high. In

![Figure 31. The CaO-FeO$_2$-SiO$_2$ system [24].](image-url)
the softening and melting test for the coarsest fraction the first rapid increase in pressure drop, usually corresponding to the first slag melting, takes place at the lowest temperature.

The temperature interval for the estimated cohesive zone will increase with increased pellet diameter both as a result of lower softening temperature for the reasons explained and as a result of the higher melting temperature of the metallic iron. The chemical analysis of hot metal and of dripping material in laboratory tests indicates that the melting temperature is increased as a result of a lower content of C. The Si content in the dripped metal is also lower in the samples with coarse pellets.

Gas utilisation—the effect of reduction rate.
The decreased gas utilisation observed, when a larger amount of coarse pellets was charged into BF No 2 at SSAB in Luleå and in pilot scale tests in the LKAB PBF is a result of the decreased reduction rate of the coarse pellets. One reason is, of course, that the lower surface to volume ratio results in a longer distance for the diffusion of reducing gas. The microscopic study of samples taken by the inclined probe indicates that the gases penetrate the same distance into the pellets, independent of pellet size. Another important reason is the large core part of the coarse oxidised pellets that contains higher amounts of magnetite, which has, for several reasons, a negative impact on reduction. The reaction rate of reduction from primary magnetite is lower than that of reduction of hematite. The porosity of the magnetite itself, as well as the wustite formed at reduction of magnetite, is lower compared to hematite and secondary magnetite, which has high micro porosity and produces a porous wustite on reduction [3][21][23]. The decreased gas utilisation will result in an increased direct reduction rate further down in the blast furnace. This means that the energy consumption increases and the carbonisation of hot metal will be delayed. The hot metal from BF No 2, as well as the dripped metal in the blast furnace simulation test at MEFOS, has a significantly decreased heat level in terms of lower C, Si and Mn contents, when pellets of 12.5-16 mm and +16mm fractions are charged compared to 9-12.5 mm fraction pellets. At BF No 2 a decreased hot metal temperature was also experienced, when charging coarser fractions of pellets.

Control of charging
The results of full-scale tests where an increased amount of coarse pellets was charged into the blast furnace, when levels in pellets bins were low, together with the knowledge gained from the study of the effect of this on the process, have resulted in considerable improvements in the particle size distribution of the pellets. In the material delivered by LKAB the proportion of 9-12.5 mm pellets has increased and is much more stable. At SSAB Luleå the personnel working with the control of the levels in silos and bins keep the levels high enough to avoid charging the coarse material into the BF. If for some reason, for example, a belt conveyer is damaged and the particle size distribution of the pellets changes, the personnel in charge of controlling the process know how to minimise the effects. The effects of the charged coarse pellets are greatly reduced by operating the blast furnace at a higher coke rate, a lower coal injection rate and slightly higher fuel rates than normal. If these precautions are taken, the adverse effects of coarse pellets on the blast furnace process will be greatly reduced.
4. **Summarised Results**

In Figure 32 the main results are summarised and an attempt to apply them to the blast furnace process has been made. The process is complex and several different phenomena must be taken into consideration at the same time. To evaluate the slag formation of the blast furnace, the slag formation in different parts has been considered. In the bosh, the fluxes have to be evenly distributed and the amount of fluxes and final slag adjusted, to avoid excessive basicity. The melting property of ordinary tuyere slag is greatly improved by addition of basic fluxes.

**Figure 32. Summary of the main results from the tests and application of them to different levels of the blast furnace.**
5. CONCLUSIONS

The influence of the degree of reduction of pellets and the addition of fluxes on the softening and melting properties of LKAB's self-fluxed and olivine pellets, and the melting points of coke and coal ashes have been studied experimentally in the laboratory. The effect of the pellet diameter of olivine pellets on reduction and softening and melting behaviour has also been studied.

The results show that the softening and melting temperatures increase and that the softening and melting temperature interval decreases with an increase of degree of reduction of the pellets.

The test results showed that adding fluxes to the self-fluxed pellets could deteriorate the softening and melting properties of the pellet. Therefore, when self-fluxed iron-bearing burden, e.g. self-fluxed pellets, is used, the top-charged fluxes will have a negative influence on the slag formation process in the blast furnace. The high basicity slag formed as a result of the reaction between liquid primary slag of self-fluxed pellet and BOF slag has a high melting point and the melting point increases when the formed slag is further reduced. This may disturb the blast furnace performance. The problems concerning slag formation when using the fluxed pellets can be avoided by adjusting both the bosh slag if necessary, by top-charging of fluxes, and the tuyere slag by injection of fluxes. At the same time a final slag of desired properties can be obtained.

Adding fluxes to the olivine pellets could improve softening and melting properties to a certain extent. The interaction between BOF slag and olivine pellets improves the melting properties of slag formed compared to the primary slag of pellet or the BOF slag itself. The negative influence on the melting properties of BOF slag by the presence of carbon will be avoided by the interaction with the olivine pellet.

Adding fluxes to the specimens of the coke and coal ashes could lower their melting points significantly. Irrespective of the types of iron-bearing burden used, injection of fluxes will improve the tuyere slag properties, thus improving the raceway conditions.

The results from the studies verify that there is a variation in the slag composition and basicity along the height of blast furnace as well as across the diameter. The use of olivine pellets and combined top charging and tuyere injection of fluxes would decrease the variation in slag composition along the height of the blast furnace, but there will still be local variations of slag composition in the burden.

The negative effect of coarse pellets on the blast furnace process has been verified both in full-scale tests, pilot-scale tests and laboratory tests. It has been concluded that the negative effect on the BF process was caused originally by an increased amount of residual magnetite in the core of the coarse oxidised pellets. This resulted in a decreased reduction rate, a more reduced pellet strength and an increase in swelling during reduction, a higher FeO content of the pellet core, an increased direct reduction and an increased temperature interval of cohesive zone with increased pellets size.
6. Future Work

The effect of basic fluxes on the melting properties of self-fluxed pellets and olivine pellets has been stated. The interaction between fluxes and pellets has been partly explained by morphological studies of the tests samples. Further studies might be able to explain the interaction to a greater degree.

The effect of fluxes on the melting properties of tuyere slag has been evaluated by melting point measurements using a high temperature microscope and by DTA. The results have to be further verified by theoretical estimations and by other laboratory test methods.

The BOF slag was found to be the best alternative when fluxes were added by tuyere injection. This decreases the melting point and the softening and melting temperature interval for all injection levels tested. In future, the effect of BOF slag and other injectants on the combustion of PCI should be evaluated. The different melting behaviour of BOF slag, depending on the presence of C, has been established, but the phenomena causing the differences has to be investigated further.

A successful two week trial at the LKAB PBF at MEFOS was carried out in November 2000. The work was part of MEFOS project and financed by Jernkontoret, SSAB Tunnplåt AB and LKAB. Results from these tests will be published. The laboratory tests and the pilot plant tests show that new concepts for BF operation can be developed in the future. The slag formation can be optimised in the bosh as well as in the raceway by top charging and/or tuyere injection of fluxes, depending on the pellet type used. By optimising slag formation, the variations of hot metal composition, in terms of C and Si content, might be improved. If the injection of slag is to be used for control of the composition hot metal and/or final slag the dynamic response to changes in injection should also be studied.
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Appendix 1

Paper 1
Influence of Basic Fluxes on Slag Formation in A Blast Furnace Using LKAB Pellets

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Abstract

Based on a proposal of injecting flux into the blast furnace via tuyeres, laboratory tests of softening and melting properties of four types of LKAB pellets with and without additional flux, corresponding to the bosh slag formation, have been carried out. The melting point measurements of coke and coal ashes with and without addition of basic flux, corresponding to the tuyere slag, have also been performed.

The test results showed that the additional basic fluxes could improve softening and melting properties of olivine pellets to a certain extent, but significantly deteriorate melting properties of self-fluxed pellets. Adding fluxes into coke and coal ashes could improve melting properties considerably.

These results indicate that injection of flux via tuyere will considerably improve the slag formation process in the blast furnace using self-fluxed pellets, both at cohesive zone and the raceway, as expected.
Introduction

The use of the olivine pellets produced by LKAB, Sweden has contributed considerably to improvement of the blast furnace performances at SSAB, Luleå Works, Sweden [1]. To further improve the quality of pellets, new types of self-fluxed-pellets with high-iron content are being developed.

The laboratory test has shown that the new types of self-fluxed pellets have quite good melting properties, in terms of melting temperature and narrow interval between softening and melting temperature [2]. However, an industrial trial using a new type of self-flux pellet did not show apparent improvement of the blast furnace operation [3]. Contrarily, there were some slag formation problems during test, e.g. high and variable resistance to gas flow in the blast furnace, very high viscous slag in the slag runner etc.

Jitang Ma [4] has pointed out that the slag formation problem was caused by formation of an excessive basic slag at the cohesive zone, where the top-charged fluxes dissolved into the self-fluxed gangue content of the pellets. Accompanied with further reduction of iron oxides the melting point as well as viscosity of the high basicity bosh slag increases considerably. Inevitable segregation of the top-charged fluxes would make it even much worse. Therefore, a proposal of injecting flux into the blast furnace via tuyeres, for replacing the conventional top-charging flux, has been presented. The use of injection of flux via tuyeres will greatly optimise the slag formation process, the basicity of the slags formed along all the height of the blast furnace will be quite even and within a desired range, besides decreasing the volume of bosh slag significantly.

In the past decades, great efforts have been given to studies of slag formation. A large number of laboratory tests of softening and melting measurements of iron ores have been carried out [5-11], but few tests included the slag formers. Therefore, these results cannot provide enough information of slag formation and the melting properties of the iron ores with fluxes.

In this study, laboratory tests of softening and melting properties of four types of LKAB pellets with and without additional flux, corresponding to the formation of the bosh slag, have been carried out. The melting point measurements of coke and coal ashes with and without addition of basic flux, corresponding to the tuyere slag, have also been performed. Three types of slags, primary slag, bosh slag and tuyere slag, have been mainly concerned. The primary slag was assumed to be formed by the gangue content of pellets; The bosh slag formed by the primary slag with dissolution of additional flux; The tuyere slag formed by ashes contained in top-charged coke and tuyere-injected coal. When injection of flux used, the injected flux is also included.

Experimental Technique

Experimental Apparatus for Softening and Melting Test

The experimental apparatus is shown in Figure 1. The furnace is heated electrically by U-shape Super-Kanthal with a heating zone of about 800 mm in height. The highest working
temperature can reach 1600°C. The crucible (40 mm i.d. x 85 mm height) made of graphite or alumina, as shown in Figure 2, has 6 holes of 6 mm in diameter on the bottom, allowing dripping of the molten materials and gas through the sample bed. A balance mounted with a container is installed beneath the reaction tube for weighing the dripped materials.

Samples of the test were sandwiched by two-layer of coke. Throughout the test, a constant load of 0.9 kg/cm² was applied to the sample bed by means of a pneumatic piston rod. The pressure given by the piston and a nitrogen gas flow through sample bed were regulated via a computer – PC 1. The bed contraction, the pressure drop across the sample bed, and the weight of dripped materials as well as the temperature in the course of the experiment were measured with corresponding devices and recorded by the second computer – PC 2. After reaching the temperature expected, the sample was cooled down to ambient temperature. The whole process was under the protection of nitrogen gas with a flow rate of 7 l/min. The experimental conditions used for softening and melting tests are summarised in Table 1.

For characterising the softening and melting behaviours of the samples, the following two indices have been used:

- \( T_1 \): a temperature, at which the pressure drop and the shrinkage of the sample bed start to increase sharply; it serves as the softening temperature in this paper. Figure 3 shows one example of this temperature for Pellet MPBO;
- \( T_{sd} \): start-of-dripping temperature, at which the first droplet of the melting material dropped to the collector, it also stands for the melting temperature in the paper.

**Experimental Apparatus for Measuring Melting Point**

Figure 4 shows a schematic view of the high temperature microscope for measuring the melting point. The furnace is also heated electrically. The highest working temperature can reach 1640°C. When measuring the melting point of slag, a specimen of slag sample of 3 mm in height and 2mmx2 mm in cross section area was placed on an alumina sample holder in the furnace and heated up gradually in a nitrogen gas atmosphere. A magnified contour of the specimen can be observed via a magnifier, as shown in Figure 5. A camera could be used to take photos of the contour of the specimen. Changes of the shape of the specimen during the test could be either drawn manually, according to optical observation, or recorded by the camera for determining the following characteristic temperatures:

- Softening: At which the specimen started to deform, the edges of specimen disappeared, Figure 5-b;
- Flow point: The materials flows and the height of the specimen decreases to about 1/3 of its original one, as shown in Figure 5-c. This temperature is defined as the melting temperature of the sample in this study.
Preparation of Samples

Pellets and fluxes
Four types of pellets made at LKAB were tested. The chemical analyses of these pellets as well as three types of fluxes, taken from SSAB, used in the study are shown in Table 3. Pellet A and B are self-fluxed, being developed, the former one has slightly higher CaO content, but lower MgO content than the latter one. MPBO and KPBO are olivine pellets, differ from each other in CaO content slightly.

Samples of the self-fluxed pellets were pre-reduced to reduction degrees 60, 75 and 90 in percentage under conditions of 850°C and 55%N2-40%CO-5%H2 reducing gas (cracks of pellets during the reduction could be avoided to a large extent). Olivine pellets were pre-reduced at a temperature of 950°C with the same reducing gases. Accordingly, BOF-slag used was also pre-reduced under the same conditions.

Considering the amount used and segregation of the BOF-slag in the blast furnace, 5% or 10% of BOF-slag in weight of pellet were added into the samples. Three different placements of BOF-slag in the pellet bed were used, as shown in Figure 6.

Coke and coal ashes
As mentioned early, the tuyere slag in this study was considered to be formed by the ashes of coke and coal burnt in front of tuyere. When injection of flux is assumed, the injected flux should be included. To make test specimens similar to the actual tuyere slag, the specimens were made of mixtures of coke and coal ashes, with or without additions of fluxes. The ratios of these materials used were different, according to different injection levels of coal and flux. Coke and coal ashes used were obtained by burning coke and coal, taken from SSAB, slowly up to 800°C in a furnace in the coal and coke laboratory of SSAB.

Three levels of coal injection and five levels of flux injection, no injection, low (L), medium (M), high (H), very high (VH), were considered in the tests as shown in Table 4. The amounts of different types of fluxes used were different, determined on the basis of obtaining five levels of same basicity of B2 (CaO/SiO2) of the tuyere slag, as that of BOF-slag used. The compositions of the specimens used are listed in Table 5.

Experimental Results

Softening and Melting Properties of Pellets
Softening and melting tests of pellets were carried out mainly in graphite crucible. Pellet samples were sandwiched by two layers of coke.

As shown in Figure 7, these two new types of self-fluxed pellets have lower softening and melting temperatures than that of olivine pellets. However, the temperature intervals between the softening and melting of the self-fluxed pellets are narrower than that of the olivine pellets tested.
The test results also show that the softening and melting temperatures increase with the increase of the pre-reduction degree, as shown in Figure 8.

**Melting Property of BOF-slag**

Softening and melting tests of BOF-slag were carried out in two types of crucibles, graphite and alumina. Table 6 shows the test conditions and results.

The results indicate that the melting property of BOF-slag is strongly dependent on the presence of carbon. When BOF-slag is sandwiched by two-layer of coke in a graphite crucible, it does not melt down at all up to a temperature 1500°C. Contrary, when using alumina crucible, the measured softening temperature BOF-slag is only about 1343 °C, and it starts dripping at a temperature 1400°C.

These results indicate that the carbon has an important role in the melting process of BOF-slag. Therefore, in order to obtain the results in relevant to the conditions in the blast furnace, graphite crucible and two-layer of coke, putting at the up and bottom of the samples, were used in the all latter softening and melting tests.

**Influence of Fluxes on the Melting Property of Pellets**

The test results showed that the effects of fluxes on the softening and melting properties of pellets were different, depending on the type of pellets and of the fluxes used.

**Influence of BOF-slag on self-fluxed pellets**

Generally, BOF-slag could increase the melting temperature of the self-fluxed pellet considerably and softening temperature slightly. The changes of the melting temperature were related to the distribution of BOF-slag in the pellet bed.

As shown in Figure 9, when BOF-slag is evenly distributed in the pellet bed, the melting temperature increases dramatically by more than 80°C. Not any dripping material is collected at temperature up to 1500 °C. It seems that the BOF-slag can block the dripping process entirely during the tests. Therefore, melting point is not obtained. When the BOF-slag was unevenly placed in the sample bed, the melting temperature increases by about 50°C, and the amount of the dripped metallic iron collected is decreased. When it was uniformly placed beneath the pellet layer, no change of melting temperature of the pellets can be seen. However, some white-gray powders could be found in the crucible after the tests for the latter two cases. A preliminary X-ray diffraction analyses showed that the white-gray powder contained di-calcium silicate (Ca2SiO4), and other complex compounds, e.g. 3CaO•Al2O3, 3CaO•SiO2 etc. TGA test showed that the melting temperature of the powder was higher than 1600°C, much higher than that of pellets and BOF-slag. These results indicate that some compounds with very high melting points, e.g. di-calcium silicate- (melting point ~2100 C), were formed during the test. The mechanism of generation of these powders and their influences on the slag properties remain to be further studied.

**Influence of BOF-slag on olivine pellets**

As shown in Figure 10, in general, additional BOF-slag decreases the melting temperature of samples for pellets of 75 and 90% pre-reduction degree, but has little effect on the softening
temperature. Adding 5% BOF-slag to pellet bed give more influence on the decrease of the melting temperature than adding 10% BOF-slag. It is also found that the flux gives more influence on the melting temperature than on the softening temperature.

Influences of some other basic additions
Tests of adding limestone and burnt dolomite to sample bed of pellet A were also conducted. The basicity $B_2 - \frac{CaO}{SiO_2}$ or $B_3 - \frac{(CaO+MgO)}{SiO_2}$ of the samples were adjusted to be the same as that of adding of 5% BOF-slag, respectively. The pellets used were pre-reduced to a degree of 75%. Slag formers were evenly distributed in the pellet bed.

The results showed that limestone or burnt dolomite could increase melting temperature of pellet A by about 30°C and 25°C, respectively, much less influence than BOF-slag. The reasons will be discussed later.

Some white-grey powders could also be found in the sample bed after the experiment. However, the amount is too little to make further examination.

Tests of the olivine pellets with the addition of lime were carried out too. The basicity of $B_2$ of the slag was the same as that of adding 10% of BOF-slag. The results showed that the influence of the lime on softening and melting temperature was similar to that of adding BOF-slag.

Melting Points of Coke, Coal ashes and BOF-slag
As shown in Figure 11, the coke ash has the highest softening and melting temperatures among those materials tested. The coal ash has much lower ones, only 1331 and 1430°C, respectively. The BOF-slag has the medium values, 1305 and 1364°C. A tuyere slag formed by a mixture of coke and coal ashes, corresponding to the condition without injecting flux, has higher softening and melting points than that of coal ash and BOF-slag alone, but lower than that of coke ash.

Effect of Fluxes on Melting Points of Coke and Coal Ashes
Addition of fluxes to coke and coal ashes, corresponding to the tuyere slags with injection of flux, can considerably lower the melting temperature and the interval between the softening and melting temperatures, as shown in Figure 11 and Figure 12. However, the changes of the melting temperature varied with the types and the amounts of the fluxes used.

Generally, the melting temperature of the specimens decreases significantly with the increase of the addition of BOF-slag or lime, until up to the “high” level. Further increasing the addition of BOF slag and lime to the “very high” level will increase the melting point of the specimen slightly.

Adding dolomite to a “low” injection level decreases its melting point considerably. However, further increasing the additions will increase its melting point, as shown in Figure 12.


Discussion

Melting Properties of Pellets and BOF-slag

The test results showed that these two types of self-fluxes pellets both had higher softening temperature, lower melting temperature and therefore narrower intervals between these two temperatures than that of olivine pellets

According to its chemical composition as shown in Table 7, the primary slag, formed by gangue content of pellet A, is located at a low melting temperature region in a ternary system of CaO-SiO$_2$-MgO with 10% Al$_2$O$_3$, as point A shown in Figure 13 (a). Its melting point is estimated to be about ~1300 °C. Since its basicity B2 is about 1, its viscosity is also supposed to be quite low. A good dripping property of the sample obtained could be one of the evidences. Therefore, the pellet A itself should not be the cause of slag formation problem.

Contrary, the melting properties of BOF-slag were changeable, in presence of carbon, as it is in the blast furnace. Its melting point could be increased dramatically, also with a very bad dripping property. These phenomena can be considered as a result of reduction of the FeO in the slag by carbon. As the basicity B2 of the BOF slag is about 4, decrease of FeO content would significantly increase its melting point. Chemical analysis of the BOF-slag after the tests up to 1500°C showed that the FeO and Fe$_2$O$_3$ in the slag were only 5.3% and 1.5%, respectively, while the original ones were 16.4% and 8.08%, respectively. The melting temperature of the BOF-slag after the tests, according to our measurement result, was higher than 1520°C, much higher than that of the original BOF-slag, about 1400°C.

Causes of Troublesome Melting Process when Adding Fluxes to Self-fluxed Pellet Bed

With dissolution of flux into the self-fluxed primary slag of pellets, the basicity of slag formed increases accordingly. If the inevitable segregation of top-charged flux is considered, the slag formed could have very high basicity locally. Table 7 lists some calculated composition of slags, based on the samples used. Bosh slag 1-2 are two slags formed by the gangue content of pellet A and 5% BOF-slag added, with no FeO content and about 10% FeO content, respectively. Bosh slag 4 formed by 10% BOF-slag and pellet A without FeO content, representing the case with segregation of BOF-slag. The basicities of B2 of the bosh slags formed can reach up to 1.87 and 2.36, the same as or very close to the basicity 2 of di-calcium silicate (2CaO.SiO$_2$, B2= 1.87).

As shown in Figure 13 (a) both bosh slag 1 (A1) and 3 (A2) have much higher melting point than that of A.

In addition, reduction of FeO can significantly change its melting point at this range of slag basicity. As shown in Figure 13(b), when basicity B2 is greater than 1, decrease of FeO can increase melting point considerably. With decrease of FeO content, the high melting point of the bosh slag 2 will further increase its melting point dramatically. Therefore, adding BOF-slag into the samples will bring twofold effects on melting properties: 1) Increase melting point by an increased basicity; 2) Further increase melting point by reduction of FeO in this region. In this case, formation of a very high melting point of di-calcium silicate is quite possible.

7
Improvement of the Melting Process when Adding Flux to the Olivine Pellets

Both MPBO and KPBO pellets contain high MgO, but with a low ratio of CaO/SiO2, quite different with that of self-fluxed pellets. Table 8 shows the chemical composition of some slags supposed to be formed during melting process when using pellet MPBO. Bosh slag 1 and 2 represent the slags adding 5 and 10% BOF-slag, respectively. The primary slag has an estimated melting point about 1600°C, point M in Figure 13-a. When adding 5 or 10% of BOF-slag, the basicity of slags formed increases as shown in Table 8. Accordingly, the melting point of slag decreased to be about 1350°C and 1550°C, as points M1 and M2 of Figure 13-a. Therefore, adding 5% BOF-slag can considerably improve the melting property. However, adding 10% gives less effect. Further increase CaO content may increase its melting point dramatically, due to the increase of the slag basicity.

Enhancing the Melting of Coke and Coal Ashes when Adding Flux

The coke and coal ashes contain mainly the acid components, Al2O3 and SiO2. Their melting points are generally high, also with a very high viscosity. For instance, the melting point of a specimen, corresponding to a tuyere slag formed by a mixture of coke and coal ashes was about 1600°C. When adding flux to the specimen, the acid components would be neutralised. The basicity of the slags formed would be increased with increase of the additions. When using “high” or “very high” level addition, the basicity B2 would be around 1.0, much close to a normal final slag in the blast furnace. Its estimated melting point is only about 1300°C, much lower than the original one. In additions, we can expect that its viscosity would be also quite low.

The BOF-slag has a different effect compared to lime and dolomite on lowering the melting point of the coke and coal ashes. This may be due to the differences mainly in MgO and Al2O3 content of the specimens and contents of some other oxides, as for example iron oxides and manganese oxides, in the BOF-slag.

Influence of Fluxes on Slag Formation Process

The slag formation in the blast furnace is a complex process, involving the softening and melting of burden, dissolution of slag formers and additives in the primary slag, absorption of ashes of fuels by bosh slag, and various chemical reactions, etc.

The major objective of using fluxes in the blast furnace process is to neutralise the gangue of iron ores and ashes of fuels. However, most of ash of fuels releases only at the time when fuels are burnt in front of tuyeres. Therefore, the bosh slag has a higher basicity than that of the primary and final slags. When the basicity of bosh slag is high, considerable changes of the slag property during the transformations from primary slag to bosh slag and from bosh slag to final slag occur. Obviously, the influence of flux on the slag formation process is dependent on iron-bearing burden used and the way of supplying flux into the blast furnace process.

When acid pellets are used, the top-charged flux would neutralise the acid components in the burden, generally improving its melting properties until reaching a certain limit, above this limit the slag property may still become worse. Contrary, when self-fluxed pellets are used, the top-charged flux would generally make the bosh slag an excessive basicity, giving a quite
negative effect on melting properties. In order to avoid an excessive basic slag formed at the cohesive zone and a very acid slag formed in front of tuyeres, injection of certain amount of flux into the blast furnace can be a good solution.

**Conclusions**

The influences of the fluxes on the softening and melting properties of LKAB self-fluxed and olivine pellets and the melting point of coke and coal ashes have been studied experimentally in the laboratory. The test results showed that adding flux to the self-fluxed pellets could worsen the softening and melting property of the pellet; while adding flux to the olivine pellets could improve softening and melting property until to a certain limit. Adding flux to the specimen of the coke and coal ashes could lower its melting points significantly.

Therefore, when self-fluxed iron-bearing burden e.g. self-fluxed pellets are used the top-charged fluxes will give very negative influence on the slag formation process in the blast furnace. On the contrary, when olivine pellets are used, the top-charged flux will generally improve the slag formation process.

Irrespective of the types of iron-bearing burden used, injection of flux will improve the tuyere slag property, thus improving the raceway conditions.

**Acknowledgements**

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**References**


Figures

Figure 1. Schematic view of experimental apparatus

Figure 2. Placement of samples in the furnace tube

Figure 3. Definition of the softening temperature
Figure 4. Schematic view of the high temperature microscope for measuring the melting point

Figure 5. Changes of contour of the specimen during a test

a. Original sample  b. Softening  c. Flow out

1: Sample holder  2: Contour of specimen

Figure 6. Three different placements of BOF-slag in pellets bed, a) layered pellets and BOF-slag; b) even mixture; c) uneven mixture.
Figure 7. Softening and melting temperature of different pellets tested (pre-reduction degree of pellet = 75%).

Figure 8. Variations of softening and melting temperature with the changes of pre-reduction degree of pellets.

Figure 9. Melting properties of Pellet A with three different placements of BOF-slag (5%).
Figure 10. Variation of the Softening and melting temperatures of MPBO and KPBO with the addition of BOF-slag (Pre-reduction degree of pellets = 75%).

Figure 11. Variations of the softening and melting temperatures of slag with the increase of BOF-slag addition; C: Coke ash; C': Coal ash; L, M, H, VH represent four levels of flux injection; BOF: BOF-slag.

Figure 12. Melting temperature of specimens with changes of flux added
Figure 13. Phase diagrams

a) System of CaO-SiO2-MgO-Al2O3 system [13]

b) System of CaO-SiO2-FeO [14]
# Tables

Table 1. Summary of test conditions

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<thead>
<tr>
<th>Sample bed diameter</th>
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<td>Particle size</td>
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<td>BOF-Slag, burnt dolomite and limestone 3 ~ 6 mm</td>
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<td></td>
<td>Coke breeze 6 ~ 9 mm</td>
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<td>Pellets weight of each test</td>
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Table 2. Pre-reduction degree of BOF-slag

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Table 3. Chemical analysis of materials used

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Table 4. Injection rate of flux and coal, kg/THM*

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* THM: Tonne of hot metal
Table 5. Composition of the specimens used (wt%)

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</table>

No, Low, Medium, High, Very high: represent the injection levels of flux
B2=CaO/SiO2; B4=(CaO+MgO)/(SiO2+Al2O3) on molar basis.

Table 6. Softening and melting test results of BOF-slag

<table>
<thead>
<tr>
<th>No.</th>
<th>Sample</th>
<th>Crucible</th>
<th>Coke</th>
<th>T1, °C</th>
<th>Tsd, °C</th>
<th>Tmax, °C*</th>
<th>Dripping</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>BOF-slag</td>
<td>Alumina</td>
<td>No</td>
<td>1343</td>
<td>1400</td>
<td>1520</td>
<td>Yes</td>
</tr>
<tr>
<td>2</td>
<td>BOF-slag</td>
<td>Graphite</td>
<td>Yes</td>
<td>-</td>
<td>-</td>
<td>1500</td>
<td>No</td>
</tr>
</tbody>
</table>

*: The maximum temperature reached during the test.

Table 7. Chemical composition of slag with pellet A

<table>
<thead>
<tr>
<th>Slag</th>
<th>Composition, wt%</th>
<th>CaO/SiO2</th>
<th>CaO</th>
<th>MgO</th>
<th>SiO2</th>
<th>Al2O3</th>
<th>FeO</th>
<th>TiO2</th>
<th>(CaO+MgO)</th>
<th>SiO2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>30.37</td>
<td>12.09</td>
<td>24.73</td>
<td>32.75</td>
<td>38.75</td>
<td>14.67</td>
<td>22.56</td>
<td>27.97</td>
<td>31.92</td>
<td></td>
</tr>
<tr>
<td>BOF</td>
<td>41.09</td>
<td>30.37</td>
<td>18.03</td>
<td>24.73</td>
<td>32.75</td>
<td>15.27</td>
<td>1.41</td>
<td>1.46</td>
<td>1.49</td>
<td>9.83</td>
</tr>
<tr>
<td>Bosh 1</td>
<td>41.03</td>
<td>25.49</td>
<td>15.43</td>
<td>11.22</td>
<td>8.08</td>
<td>21.88</td>
<td>19.20</td>
<td>17.12</td>
<td>15.49</td>
<td>19.82</td>
</tr>
<tr>
<td>Bosh 2</td>
<td>41.03</td>
<td>25.49</td>
<td>15.43</td>
<td>11.22</td>
<td>8.08</td>
<td>21.88</td>
<td>19.20</td>
<td>17.12</td>
<td>15.49</td>
<td>19.82</td>
</tr>
<tr>
<td>Bosh 3</td>
<td>41.03</td>
<td>25.49</td>
<td>15.43</td>
<td>11.22</td>
<td>8.08</td>
<td>21.88</td>
<td>19.20</td>
<td>17.12</td>
<td>15.49</td>
<td>19.82</td>
</tr>
<tr>
<td>Bosh 4</td>
<td>41.03</td>
<td>25.49</td>
<td>15.43</td>
<td>11.22</td>
<td>8.08</td>
<td>21.88</td>
<td>19.20</td>
<td>17.12</td>
<td>15.49</td>
<td>19.82</td>
</tr>
</tbody>
</table>

Table 8. Chemical composition of slag with pellet MPBO

<table>
<thead>
<tr>
<th>Slag</th>
<th>Composition, wt%</th>
<th>CaO/SiO2</th>
<th>CaO</th>
<th>MgO</th>
<th>SiO2</th>
<th>Al2O3</th>
<th>FeO</th>
<th>TiO2</th>
<th>(CaO+MgO)</th>
<th>SiO2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>5.01</td>
<td>28.52</td>
<td>37.38</td>
<td>8.29</td>
<td>15.41</td>
<td>5.39</td>
<td>0.13</td>
<td>0.89</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BOF</td>
<td>41.09</td>
<td>9.84</td>
<td>12.97</td>
<td>0.95</td>
<td>16.40</td>
<td>1.89</td>
<td>4.18</td>
<td>5.49</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bosh slag 1</td>
<td>27.13</td>
<td>26.49</td>
<td>34.76</td>
<td>6.61</td>
<td>0.00</td>
<td>5.03</td>
<td>0.78</td>
<td>1.54</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bosh slag 2</td>
<td>36.63</td>
<td>23.25</td>
<td>30.53</td>
<td>5.18</td>
<td>0.00</td>
<td>4.42</td>
<td>1.20</td>
<td>1.96</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

17
EFFECT OF FLUXES ON SLAG FORMATION IN A BLAST FURNACE BY TOP CHARGING AND TUYERE INJECTION

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* SSAB, Tunnplåt AB, Luleå, Sweden
** Division of Process Metallurgy, Luleå University of Technology, Sweden;

Synopsis: Based on a proposal for injecting fluxes into the blast furnace via tuyeres an evaluation of the influence of fluxes top-charged or tuyere-injected into a blast furnace has been done. The interaction between the slag formers and pellets in the lower part of the shaft and in the cohesive zone of the blast furnace was studied. Chemical analyses, melting point measurements and morphological studies were carried out on samples from previous laboratory softening and melting tests as well as on samples from the LKAB pilot blast furnace at MEFOS. The slag formation mechanism in the blast furnace is discussed.

The results show that interaction between olivine pellet and BOF slag may cause variations in slag composition and slag properties at different levels in the blast furnace as well as at different radial positions. The results indicate that the deteriorated melting properties of fluxed pellets by adding BOF slag are caused by formation of a high basicity slag. The negative effect on slag formation caused by top charged fluxes might be avoided by injection of fluxes through the tuyeres.

Keywords: slag formation, fluxes, injection, pellets, excavation

1. Introduction

SSAB in Luleå has been using olivine pellets produced by a Swedish iron ore company, LKAB, since 1982. Considerable improvements of the blast furnace performance have been obtained partly as a result of the good metallurgical properties of the olivine pellets [1], e.g., high iron content, low gangue content, high meltdown temperature and a narrow softening and melting temperature interval etc. The slag volume of the blast furnaces in Luleå is low, only 150-165 kg/THM, even so with recycling of cold-bonded briquettes and an increased ash content of coke. The 1999 average productivity of BF No.2 with a useful volume of 1253 m$^3$ was 3.2 tonnes per cubic meter of working volume and 24 hours.

In order to achieve even better performance of the blast furnace, a new type of pellets — self-fluxed pellets have been under development, which have better metallurgical properties [2], e.g., lower gangue content, narrower softening and melting temperature interval etc. However, industrial trials using this type of self-fluxed pellets did not show any improvement of the blast furnace performance. Contrarily, it caused some difficulties for smooth control of the blast furnace operation, e.g., low permeability of the burden column, problematic tapping etc. One of the reasons has been theoretically attributed to problematic slag formation process in the furnace by Ma [3]. When top-charging self-fluxed pellets together with basic flux, an excessive basic slag can form in the cohesive zone, where the top-charged basic fluxes partly dissolve into the primary slag of pellets. The newly formed slag can have a very high melting point and a low fluidity, which can even result in the re-solidification of the slag. As a result, the permeability of the cohesive zone and of the bosh region becomes worse. A proposal for injecting basic flux via tuyeres instead of top charging has also been made for enhancing the slag formation process and therefore the blast furnace operation.

To find out the influence of the basic flux on the slag formation in the blast furnace softening and melting tests of self-fluxed and olivine pellets as well as melting point tests of coke and coal ashes, with and without the addition of basic fluxes were conducted in the laboratory [4]. The experimental results show that the addition of basic flux to olivine pellets can enhance the melting properties of the pellets. Contrarily, the addition of basic flux to self-fluxed pellets can significantly deteriorate the melting properties of the pellets. By adding basic flux to a mixture of coke and coal ashes their melting points can decrease. However, the slag formation mechanism has not been sufficiently studied. To find out the slag formation mechanism, further morphological study of the samples from the softening and melting tests is of interest.

Trials of injecting basic fluxes via tuyere were also carried out in the LKAB pilot blast furnace at MEFOS (Metallurgical research foundation in Luleå). The furnace has an effective volume of 8 m$^3$ and is equipped with
three probes for taking solid samples as well as measuring gas temperature and composition in the furnace. Samples from probes during operation and from dissection of the furnace have been obtained. Studies of these samples can also be quite helpful to get knowledge of the slag formation mechanism in the furnace. Therefore, the major objective of this work was supposed to find out the slag formation mechanism by studying changes of pellets and fluxes, especially BOF slag, in structure during the softening and melting experiments and in the pilot blast furnace.

2. Experimental

2.1. Sample Material

The chemical composition of the original materials used for the softening and melting tests or charged into the LKAB pilot blast furnace (hereafter called PBF) at MEFOS is shown in Table 1.

2.2. Excavation Samples from the Pilot Blast Furnace

The pilot blast furnace was equipped with a bell top charging system without movable armour during this period. The fluxes, limestone, BOF slag and quartzite were top charged. At nitrogen quenching after 1st campaign the furnace was on all-coke operation with a pellet burden consisting of 100% MPBO. In the 2nd campaign coal injection was used and the pellet burden consisted of 100% KPBO. To avoid a heat flow upward after interruption of the blast, the nitrogen was added from the top at the first period of cooling. When the burden had cooled down the excavation of blast furnace burden was made. A series of samples was taken from each pellet layer, across the diameter of the blast furnace, starting from 9th pellet layer from the top of furnace. Each sample was about 3-5 litres.

The samples from the upper part, where the materials still were lumpy, were divided into separate samples of each material and the ratio of BOF slag in each position was calculated after weighing. The samples from the lower part contained materials that were more or less aggregated. These samples were studied by chemical analyses, melting point measurements, optical microscope and SEM analyses.

2.3. Probe Samples from the PBF

With the inclined burden probe samples were taken from the lower shaft during operation. The samples were divided into sub-samples depending on their radial position in furnace. Samples were taken during operation with
- 70%MPBO/30%KPBO with top-charging with and without tuyere injection of fluxes
- Pellet C with top-charging of fluxes

3. Experimental Results

3.1. Samples from Softening and Melting Tests

Samples from softening and melting tests were studied by SEM analyses. Figure 1 shows an image of a sample consisting of Pellet A and BOF slag after softening and melting test up to a maximum temperature of about 1550°C. The iron oxide in the pellet is reduced to metallic iron that is found at the top of the crucible after finished test. Below it, there are residuals of BOF slag and further down a second slag of other chemical composition. At the bottom, mixed with the coke a third slag is found. The SEM images of the second and third slag phases are shown in Figure 2 and

![Figure 1. Sample from a test with pellet A and BOF slag](image)
Figure 3, respectively. The metallic iron is entrained by the slag phases and the dripping is stopped. In the residuals of BOF slag two phases mainly consisting of (Ca,Si,Al)O and (Fe,Mg,Mn)O are widely spread. The chemical composition of these phases varies, e.g. (Ca,Si,Al)O, which is found also in the border of metal and BOF slag is dominated by either Si or Al. The intensity of Al is high as compared to that of BOF slag in the other samples studied. Metallic Fe and V are found in the BOF slag. The slag in the intermediate region seen in Figure 2 contains mainly (Ca,Si)O and small grains of MgO. The newly formed slag phase, found among the coke, shown in Figure 3 mainly consists of (Ca,Si,)O, with a very high amount of Ca. No FeO is detected neither in the intermediate slag nor in the slag at the bottom. A few metallic grains of Fe are found in the intermediate slag. Larger areas of FeMet are detected in the slag at the bottom. Point analyses made in SEM and XRD indicate the presence of di-calcium-silicates and tri-calcium-silicates. Concerning this matter further analyses must be made.

The zone of close contact between MPBO and BOF slag in a sample from a test interrupted at about 1400°C can be seen in Figure 4. The pellet is quite well reduced and the metal has melted together. The BOF slag consists of a matrix of (Ca,Si)O with Ca as the main component. The Si is sometimes partly exchanged for V or more seldom for Al. Ca sometimes occurs as CaO and some areas containing (Ca,Fe,V)O are also found. The Si content in the BOF slag is higher close to the pellet border. B2 of the main phase varies in the range 1.5-5.5 with an average of 2.4 in the BOF slag has decreased to 1.9 in average close to the BOF slag/pellet border. The concentration of Ca on the pellet, close to the pellet/BOF slag border, increases. As can be seen in Figure 4, B2 of the pellet slag phase has increased to about 1.6 -2.0 at the pellet/BOF slag border as compared to the maximum value of about 0.6 being found when the pellet is not in contact with the BOF slag. A high concentration of Mg, combined with Fe and sometimes also Mn, is found in the BOF slag close to the border indicating (Fe,Mg,O)O and (Fe, Mg, Mn)O. In the BOF slag (Fe,Mg,Mn)O contains much less Fe, but FeMet is present.

3.2. Excavation Samples from the PBF

3.2.1. Distribution of BOF slag

The results obtained from measuring the distribution of BOF slag in the PBF after 1st and 2nd campaign show an uneven distribution over the radius with less BOF slag found in the east. Figure 5 shows the result from 1st campaign.
3.2.2. Chemical composition

The pellets from the centre of layers 20, 21, and 23 used in this study are generally well reduced and the outer parts of the pellets have a metallic lustre. In layers 20 and 21 the pellets and slag formers are adhered to each other to some extent but had not started to melt. The material of layer 23 consists of aggregates of pellet, fluxes and coke, shown in Figure 7. Layer 23 is part of the cohesive zone, totally consisting of two pellet layers, where it can be seen that the BOF slag has started to melt. The highly reduced pellets from layer 23 are shown in Figure 6. The core of some of the pellets has shrunk and/or partly melted and dripped out. Quite often a metallic shell is surrounding a small hard core and between the core and shell a big gap is found.

Based on the chemical analyses the reduction degrees of pellet of layers 20, 21 and 23 are estimated to be about 75-85% and 96-97% of pellet cores and pellet shells, respectively. The basicities B2 and B4, 0.14 and 0.75, respectively, in the pellets charged, increase in all samples, as can be seen in Table 2. The basicity B4 increases from about 0.75 of the original material to a considerable high value for those pellet cores of layer 23 that are found close to the pellets with more or less empty cores. In Table 2 the chemical composition of the BOF slag from the centre of layers 9, 14, 21 and 23 is shown. The chemical composition of BOF slag varies - especially the Fe and MgO content. The BOF slag of layer 23 has lower basicities, B2 and B4, as compared to those of BOF slag of the layer above. At this level, where the temperature has been higher and the softening and melting of BOF slag has started, the estimated reduction degree is significantly increased to approximately 80%. From laboratory tests it is known that the reduction of BOF slag is very slow at low temperatures and that the maximum reduction degree achieved after 2 hours' reduction at 1150°C in a reducing gas composed of 55% N₂, 40% CO and 5% H₂ was 59%.

<table>
<thead>
<tr>
<th>Table 2 Chemical composition of MPBO and BOF slag from the centre of PBF after 1st Campaign.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pellet cores, layer 20</td>
</tr>
<tr>
<td>------------------------</td>
</tr>
<tr>
<td>Pellet shells, layer 20</td>
</tr>
<tr>
<td>Pellet cores, layer 21</td>
</tr>
<tr>
<td>Pellet shells, layer 21</td>
</tr>
<tr>
<td>Pellet cores, layer 23</td>
</tr>
<tr>
<td>Pellet shells, layer 23</td>
</tr>
<tr>
<td>Pellet shells, layer 23</td>
</tr>
<tr>
<td>BOF slag, layer 9</td>
</tr>
<tr>
<td>BOF slag, layer 14</td>
</tr>
<tr>
<td>BOF slag, layer 20</td>
</tr>
<tr>
<td>BOF slag, layer 21</td>
</tr>
<tr>
<td>BOF slag, layer 23</td>
</tr>
<tr>
<td>Final slag</td>
</tr>
</tbody>
</table>

* Pellets close to pellets with an empty core.

3.2.3. Melting point measurements

The results in Table 3 correspond to temperatures for three events that are also described in Figure 8.

- **Softening**: The contour of the sample gets smooth and no sharp border can be distinguished.
- **Active melting**: The melting is rapid and the shape of the specimen changes quickly.
- **Flow point**: The materials flows out and the height of the sample decreases to about 1/3 of the original one.
Table 3 Softening and melting temperatures of samples from centre of PBF.

<table>
<thead>
<tr>
<th>No</th>
<th>Sample</th>
<th>Softening</th>
<th>Active melting</th>
<th>Flow out</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pellet core, Layer 20</td>
<td>1500</td>
<td>1530</td>
<td>1547</td>
</tr>
<tr>
<td>2</td>
<td>Pellet shell, Layer 20</td>
<td>1527</td>
<td>1537</td>
<td>1547</td>
</tr>
<tr>
<td>3</td>
<td>Pellet core, Layer 21</td>
<td>1389</td>
<td>1533</td>
<td>1589</td>
</tr>
<tr>
<td>4</td>
<td>Pellet shell, Layer 21</td>
<td>1496</td>
<td>1539</td>
<td>1565</td>
</tr>
<tr>
<td>5</td>
<td>Pellet core, Layer 23 *</td>
<td>1543</td>
<td>1573</td>
<td>1634</td>
</tr>
<tr>
<td>6</td>
<td>Pellet core, Layer 23</td>
<td>1535</td>
<td>1568</td>
<td>1589</td>
</tr>
<tr>
<td>7</td>
<td>Pellet shell, Layer 23</td>
<td>1530</td>
<td>1550</td>
<td>1570</td>
</tr>
<tr>
<td>8</td>
<td>BOF slag, Layer 9</td>
<td>1306</td>
<td>1354</td>
<td>1377</td>
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<tr>
<td>9</td>
<td>BOF slag, Layer 14</td>
<td>1293</td>
<td>1323</td>
<td>1344</td>
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<tr>
<td>10</td>
<td>BOF slag, Layer 21</td>
<td>1255</td>
<td>1315</td>
<td>1334</td>
</tr>
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<td>11</td>
<td>BOF slag Layer 23</td>
<td>1288</td>
<td>1323</td>
<td>1344</td>
</tr>
<tr>
<td>12</td>
<td>Mixture of No4 and 10</td>
<td>1200</td>
<td>1257</td>
<td>1578</td>
</tr>
</tbody>
</table>

* Pellets with shrunk cores close to pellets with empty cores

As can be seen in Table 3, the cores of pellets from the centre of layers 20 and 21 start to melt at lower temperatures as compared to that of the shells. The flow points of the cores are the same or slightly higher than those of the shells. The pellet shell of layer 23 has lower softening and melting temperatures and a narrower softening and melting interval than the pellet core, of which the flow point is very high. The melting point of the BOF slag decreases slightly from layer 9 to layer 14 and further to layer 21 but increases from layer 21 to layer 23. A mixture of equal parts of BOF slag and pellet shell starts to soften and melt at temperatures of 1200°C and 1257°C respectively, but does not flow out until at 1578°C.

3.2.4. SEM analyses

Samples of pellets and BOF slag of the layers 21 and 23, respectively, were prepared for SEM studies. Some images obtained from the SEM analyses are shown in Figure 9 and Figure 10. The pellets of layer 21 have a structure consisting of metallic iron with quite a high porosity [5]. The pellets are highly reduced and, as a consequence of a low gangue content only small areas of slag are found. Pellet and BOF slag stick to each other. The BOF slag structure is quite similar to the original one and no sign of melting can be seen. As can be seen in Table 3, this sample of BOF slag starts to soften at about 1255°C and flows out at 1334°C. The phase of the BOF slag containing (Ca,Si)O (A in Figure 9) extends over large areas. In this phase Si is partly exchanged for V, more seldom for Al. Some areas of this phase have a higher intensity of Ca in form of CaO or (Ca,Fe)O. Another phase of the BOF slag, seen as distinct spherical grains (B in Figure 9) consists of (Fe,Mg)O. The border between the pellet and the BOF slag is clear but the SEM analyses indicate a slight increase of Ca at the pellet surface in contact with the BOF slag.

As expected, the shells of the pellets of layer 23 are also well reduced but the porosity of the shells is much lower as compared to that of the previous sample. The BOF slag is deformed and the melting has probably just started. Its softening temperature and flow point were measured to be 1288°C and 1344°C, respectively. The main phase in the BOF slag seems different, but the composition is still about the same as in the BOF slag of layer 21. No areas with a high intensity of Ca are detected and the distinct spherical grains of mainly (Fe,Mg)O have lost their shape and floated out. In the pellet, close to the BOF slag border, higher amounts of especially Ca, but also of Mg are found. In the slag phase of pellet Ca and Mg exist in combination with Si and sometimes also with Al. The increased contents of Ca and Mg can be seen less than about 0.5mm distance from the border into the pellet.
3.3. Study of Probe Samples

Samples from an area close to the cohesive zone were taken with the inclined probe during operation of the PBF. The exact radial position of samples on the furnace diameter is not known. Samples representing operation with MPBO/KPBO and Pellet C without injection of fluxes and MPBO/KPBO with injection of fluxes are studied in an optical microscope and in a SEM.

In general the pellets of all samples consist of a highly reduced shell of a quite high porosity, an intermediate part of sintered metallic iron and a core of wustite with some flakes of metallic iron. The core quite often includes a void. The slag amounts in the pellets are low in all samples but especially in the sample of Pellet C.

On the pellet surface as well as at the interface between adhered pellets increased amount of slag phases are found. In Figure 11 an example of a complex slag phase found on the surface of the pellet can be seen. The amount of potassium is very high in the surface slag, but decreases rapidly in the pellet slag when moving inside the pellet. The average concentrations of K in the surface slags of the samples of MPBO/KPBO without injection, of Pellet C without injection and of MPBO/KPBO with flux injection are approximately 20%, 10% and 5%, respectively. The average concentrations of K in the pellet slag phase, inside these surface slags of the same samples are approximately 13%, 2% and 2%. The components of the slag phases with high a K are mainly of Si, K, Mg and Al. The basicity of the slag in the pellet is naturally higher for the fluxed pellets as compared to that of the olivine pellets but the difference in basicities of the surface slags are not significant. SiO₂, MgO and CaO as well as S contents of slag on the MPBO/KPBO pellet surface are higher for samples taken during injection as compared to without injection.

4. Discussion

4.1. Slag formation when using olivine pellets and BOF slag

The SEM studies of softening and melting samples and of samples from the PBF show that olivine pellets and BOF slag interact during start of softening and melting only if the pellet and the BOF slag are in contact with each other. If the pellet is not in contact with the BOF slag only the components of the blast furnace gas will interact with the pellet. It means that the slag formation for different pellets in the burden will be quite different dependent if they are close to another pellets, a basic flux or an acid flux. The basicity of the slag formed at different positions in the burden can vary quite a lot in chemical composition as well as in basicity. Therefore, also slag properties such as melting temperature and viscosity will vary. The variation is even higher when an uneven distribution of fluxes is considered, too. By injection of slag formers these variations will decrease.

The SEM studies of softening and melting samples and of samples from the PBF show that there is no interaction between BOF slag and the olivine pellets before softening and melting have started. This also explains why the main effect of BOF slag was found on the melting temperature [4], and not on the softening temperature, when BOF slag was added to the pellet bed in softening and melting test. A sample consisting of equal parts of BOF slag and pellet shell of layer 21 starts to melt before 1300°C. The interaction between BOF slag and olivine pellet can probably start at about that temperature. At first an effect of interaction can be seen only on the surface of pellet and BOF slag mainly by an increased amount of Ca and Si, respectively. When the temperature is further increased higher amount of both of Ca and Mg are found in the pellet. The high basicity of BOF slag includes an excess of Ca and free CaO is found in a matrix consisting mainly of Ca and Si, but some V and Al also. This free CaO seems to move more easily and can therefore interact with the other burden materials. Mg is quite strongly bonded in the (Fe,Mg)O and (Fe,Mg,Mn)O, until Fe²⁺ is reduced to Fe₃⁺ and the BOF slag starts to melt. In layer 23 an effect on the overall chemical composition of the BOF slag can be seen and not only at the BOF slag surface. The BOF slag is deformed and has almost melted which means that the diffusion of ions increases. The core part of the pellet that sometimes melts and entrains out of the pellet can also interact with this almost melted BOF slag. The entrained slag probably includes SiO₂ and FeO as the content of these in the residuals of the core decreases, while the MgO content increases. The melting point of the residual material in the core is very high.

The changes of chemical composition of individual pellets will strongly depend on the environment. Nevertheless, there is a slight increase in the Ca content and a decrease in the Si content in the slag phase of MPBO in all samples and as a result the basicity is increased.
4.2. Slag formation when using fluxed pellets and BOF slag

The results from the study of the softening and melting sample containing fluxed pellet and BOF slag give an idea about what happened in the test. With the fluxed pellet an early melting primary slag (~1300°C) can start dripping. The results from the study of the sample from a softening and melting test show that the composition of the BOF slag has changed and that slags quite different from BOF slag are formed during the test. One of these new slags is found re-solidified at the bottom of the crucible. All three slags studied - the residual BOF slag, the intermediate slag and the new slag - could have stopped the metal from flowing down and drip out of the crucible. The slag found at the bottom of crucible mainly consisted of (Ca,Si)O of a high Ca content with lower content of Mg and Al and no FeO. The known facts indicate the course of softening and melting test to be as follows. The pellets are reduced to FeO and the primary slag containing some FeO melts and starts to drip down. The BOF slag partly dissolves into the liquid slag and the basicity of it will gradually increase. The FeO in the liquid slag is reduced to FeO. As a result, the melting point of this new slag increases more than can be compensated for by the increase of temperature during the test and the viscosity also increases. When the metallic iron finally melts and is supposed to drip down it is entrained by both the residual BOF slag pieces that has partly melted and adhered to each other as well as by the high viscosity slag at the bottom of the crucible. The XRD analysis made on the newly formed slag at the bottom of the crucible indicated that it consists of di-calcium-silicate and tri-calcium silicate. From the analyses made some approximate estimations of melting temperature can be done based on the assumption that the slag of Pellet A mainly dissolves more CaO when interacting with the BOF slag. As can be seen in Figure 12, the melting point of the newly formed slag is much higher as compared to the primary slag of the pellet (~1300°C).

4.3. Melting properties of BOF slag

Earlier studies showed that the melting properties of BOF slag could vary. Different processes having influence on the melting point of BOF slag occur. 1) Reduction of FeO from (Fe,Mg)O and (Ca,Fe)O 2) Flow of Ca and Si out from and into BOF slag respectively. 3) Direct reduction of manganese from (Mg,Mn)O. Increased FeO content of BOF slag at the first step of reduction might explain the decrease of melting temperature from layer 9 to layer 14 and further to layer 21. The reduction rate increases at higher temperatures and in layer 23 the reduction degree of the BOF slag is estimated to be approximately 80%. At the same time the basicity decreases. This combined effect and the fact that the manganese is still part of the slag phase might explain that the increase in the melting temperature is limited. It is probable that in a pellet burden consisting of olivine pellets the BOF slag will dissolve the gangue of the acid pellet as the reduction rate increases. Therefore, the increased high melting point as a result of the reduction will not disturb the slag formation process when top-charging fluxes with olivine pellets. On the other hand this will be the case with the self-fluxed pellets.

4.4. Effect on potassium recirculation by flux injection

It is difficult to be sure of the results from the probe samples as there are few samples and their exact position is not known. The results indicate that the slag adhered on the pellet surface is dependent on the materials top-charged as well as on the tuyere-injection of fluxes more than on the composition of the primary slag of pellet. Potassium is easily dissolved in an acid slag with low CaO content. However, the diffusion of K from the pellet surface into the pellet depends on the composition of the primary slag of the pellet. In studies made by Sasaki et al. [6] the potassium oxide was found to be reduced at the moment when the slag drops are separated from cohesive zone. In the case with injection of fluxes through the tuyeres the dripping slag will have a lower basicity and bind potassium oxide. This will probably limit the reduction of potassium oxide from the dripping slag and therefore also the re-circulation of potassium.
5. Conclusion

The results from the studies verify that there is a variation in the slag composition and basicity along the height of blast furnace as well as over the diameter. The use of a self-fluxed pellet and injection of fluxes through the tuyeres will make it possible to achieve a smooth slag formation with optimum slag properties in all positions in the burden. The use of olivine pellets and combined top charging and tuyere injection of fluxes would decrease the variation in slag composition along the height of the blast furnace, but there will still be local variations of slag composition in the burden.

The interaction between BOF slag and olivine pellets improves the melting properties of slag compared to the primary slag of pellet or the BOF slag itself. The negative influence on the melting properties of BOF slag by the presence of carbon will be avoided by the interaction with the olivine pellet.

The high basicity slag formed as a result of the reaction between liquid primary slag of self-fluxed pellet and BOF slag has bad melting properties and may disturb the blast furnace performance. The problems with slag formation with the fluxed pellet can be avoided by adjusting the bosh slag, if necessary, by top-charging of fluxes and the tuyere slag by injection of fluxes, at the same time obtaining a final slag of desired properties.

Acknowledgements

We are grateful to Magnus Andersson LKAB, Johan Eriksson and Birgitta Nyberg at Luleå University of Technology for their assistance in measurements and Tonny Eriksson at SSAB for his help with the samples from PBF. We also want to thank SSAB, LKAB and Jernkontoret for their support in the project. Special thanks to Professor Jitang Ma that primarily presented the idea on which our work is based and has supported us in planning and discussions.

References

Appendix 3

Paper 3
The Effect on Blast furnace Process of changed Pellet Size as a Result of segregation in Raw Material Handling.

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Key Words. Pellets, Blast Furnace, Reduction, Swelling

INTRODUCTION

SSAB Tunnplåt in Luleå had two blast furnaces in operation until June 2000. BF No 1 produced about 650,000 tonnes/year and BF No 2 produced about 1,350,000 tonnes/year. In the summer of 2000 BF No 2 was rebuilt and the new blast furnace, BF No 3, has replaced both existing furnaces. The production of the newly started BF No 3 will be about 2,200,000 tonnes/year. Data for the two old blast furnaces and the new BF No 3 are listed in Table I. The ferrous burden charged into the blast furnaces at SSAB Tunnplåt in Luleå has consisted of 100% pellets since 1978, when the sinter plant was closed down. The average pellet burden is two thirds MPBO (Olivine pellets from LKAB Malmberget) and one third KPBO (Olivine pellets from LKAB Kiruna). The pellets are delivered daily to Luleå by train from Malmberget and Kiruna. The chemical composition of MPBO and KPBO is quite similar, but as can be seen in Table II, KPBO contains slightly more CaO. Table III shows the average of

<table>
<thead>
<tr>
<th>Year of erection</th>
<th>BF No.1</th>
<th>BF No.2</th>
<th>BF No.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design</td>
<td>Brassert/Voest</td>
<td>Demag</td>
<td>SSAB/Kvaerner</td>
</tr>
<tr>
<td>Hearth diameter</td>
<td>7.5</td>
<td>8.5</td>
<td>11.4</td>
</tr>
<tr>
<td>Working volume</td>
<td>890</td>
<td>1290</td>
<td>2400</td>
</tr>
<tr>
<td>Total volume</td>
<td>1109</td>
<td>1590</td>
<td>2850</td>
</tr>
<tr>
<td>No of tuyeres</td>
<td>18</td>
<td>24</td>
<td>32</td>
</tr>
<tr>
<td>No of tap holes</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Top pressure</td>
<td>10</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>Charging equipment</td>
<td>Skip/Bell McKee</td>
<td>Belt/Bell less top Central Feed</td>
<td>Belt/Bell less top Central Feed</td>
</tr>
<tr>
<td>Daily output</td>
<td>2000</td>
<td>4200</td>
<td>6700</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pellet</th>
<th>Fe</th>
<th>FeO</th>
<th>CaO</th>
<th>SiO₂</th>
<th>MgO</th>
<th>Al₂O₃</th>
<th>CaO/SiO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPBO</td>
<td>66.7</td>
<td>0.7</td>
<td>0.25</td>
<td>1.95</td>
<td>1.45</td>
<td>0.40</td>
<td>0.13</td>
</tr>
<tr>
<td>KPBO</td>
<td>66.5</td>
<td>0.4</td>
<td>0.50</td>
<td>2.15</td>
<td>1.55</td>
<td>0.22</td>
<td>0.24</td>
</tr>
</tbody>
</table>
burden materials charged into the blast furnaces during 1999. The ratios of different pellet types to the two blast furnaces can differ from time to time, depending on availability and process conditions. The high productivity and the low slag volumes achieved are mainly attributable to the low gangue content and the good metallurgical properties of the olivine pellets, but also to the relatively low ash content of coke.

Decreased filling levels in pellet bins at BF No 2 at SSAB Luleå have resulted in severe process disturbances on a number of occasions during recent years. These disturbances are shown by changes in burden permeability and gas utilisation followed by slips and changed heat level of hot metal. Traditionally, the explanation for this has been an increased amount of fines entering the blast furnace. Practical studies were carried out on the bunkers of Blast Furnace No 2 in Luleå. Contrary to what was expected, these experiments showed no increase in the amount of fines charged to the blast furnace but an accumulation of coarse material at low bunker levels.

In one earlier laboratory study it was discovered that pellet size has a pronounced effect on low-temperature reducibility as well as high-temperature reducibility and strength as a result of heterogeneous structure [1]. Another study reported the same results concerning large pellets having lower reducibility and also causing lower resistance to gas flow during reduction [2]. The latter study also claimed the dependency of pellet diameter on the quality – in terms of increased low temperature breakdown (LTB) – of pellets indurate in the bottom layer on straight grate pellet machine. The negative effect on LTB was strongly dependent on pellet diameter. The low temperature breakdown was much higher for the large pellets than for normal sized ones.

To verify that the disturbances on the blast furnace process were caused by the coarse fraction of pellets, tests with controlled charging of different pellet fractions were carried out at the LKAB pilot blast furnace (hereafter called PBF) at MEFOS (Metallurgical Research Centre in Luleå). The experiments confirmed that a high ratio of pellets +12.5 mm caused production disturbances. The effect was also studied in laboratory tests – reduction and softening and melting tests – on different size fractions of pellets to determine why the coarser fractions cause these process disturbances. An evaluation of the laboratory tests as well as the data from the tests in the experimental blast furnace has been made.

**EXPERIMENTS**

**Process disturbances when charging coarse pellets**

Low filling levels in pellet silos and pellet bins have caused several severe disturbances of the blast furnace process over the years. These disturbances included low gas utilisation, large variations in permeability of burden column, large variations of heat load, low hot metal temperature, low chemical energy of hot metal and series of slips. A focus on these phenomena has reduced both the frequency and seriousness of the disturbances. Three quite recent examples of the influence on the blast furnace process of BF No 2, when charging pellets with a particle size distribution containing higher ratios of the fractions 12.5-16mm and +16mm, as compared to what is normally charged will be described briefly in this paper. The blast furnace was
operated under different process conditions on these three occasions and different actions were taken to stabilise the process.

- Coal injection of 155kg/thm - Action = increased fuel rate in the form of increased coal injection rate.
- Coal injection of 120kg/thm - Action = all-coke operation
- All-coke operation - No action taken

In the first example the increased amount of coarse pellets is a result of low levels in one of the pellet silos and low levels in all pellet bins, which persists for about 24 hours. The effect on the process includes low gas utilisation, variations in burden permeability, increased direct reduction rate and variations in heat load of the bosh. The largest change in heat load is seen in the lowest staves row and after a period with low values, slips occur. In spite of an increased fuel rate the Si and C contents of the hot metal as well as the hot metal temperature, have decreased.

In the second example the filling levels in the pellet bins are decreased to values of about 25-30%. The effects observed on the process are a decreased gas utilisation and increased variations in burden permeability followed by increased variations in heat load. All-coke operation is introduced and the process is stabilised, but some effects can be seen in the form of a decreased hot metal temperature and contents of Si and C of hot metal.

In the third example one of the pellet silos is emptied and the particle size distribution of pellets is changed to only about 59% fraction 9-12.5mm pellets and about 38% fraction 12.5-16mm pellets. The blast furnace is on all-coke operation when these pellets are charged. The only effect that can be seen on the blast furnace process is a decrease in gas utilisation of two units.

**Full-scale test - emptying of pellet bins.**

Two different pellet bins are emptied and pellet samples are taken at the outlet side of the screen. The samples represent the material entering the blast furnace. The filling levels at start are about 64% on the first occasion and about 80% on the second occasion. No new material is filled into the bin during the test. Totally, about 60 samples are taken at each trial. The frequency of sampling is increased with a decreased filling level of the pellet bin. In both tests all samples are analysed for particle size distribution and every fourth sample for moisture content. In the second test the bulk density is measured and a video of material movement is recorded. The original particle size distribution of KPBO and MPBO is found in Table IV.

![Figure 1. Change of particle size distribution of pellets during the second test of emptying a pellet bin.](image)

<table>
<thead>
<tr>
<th>Filling level, %</th>
<th>MPBO</th>
<th>KPBO</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>40</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

The test results show that an increased amount of fines does not enter the blast furnace at low filling levels in pellet bins. A lot of fines have accumulated in the pellet bin; to such an extent that the return fines belt conveyor stops. In spite of this the samples taken do not show any increased amount of fines, indicating that the sieves operate efficiently. The screening analyses show an increased amount of pellets in fractions 12.5-16mm and +16mm when the filling level was about 43% and 37%, respectively. In Figure 1, the result from the second test is shown. As a result of material falling from the walls into the bin, the filling level sometimes increases during the test. The video shows that the material falling from the walls contains both fines and

---

**Table IV. Original particle size distribution of pellets.**

<table>
<thead>
<tr>
<th>Particle size</th>
<th>MPBO</th>
<th>KPBO</th>
</tr>
</thead>
<tbody>
<tr>
<td>+16mm</td>
<td>2%</td>
<td>1%</td>
</tr>
<tr>
<td>12.5-16mm</td>
<td>20%</td>
<td>11%</td>
</tr>
<tr>
<td>9-12.5mm</td>
<td>75%</td>
<td>85%</td>
</tr>
<tr>
<td>5-9mm</td>
<td>2%</td>
<td>2%</td>
</tr>
<tr>
<td>-5mm</td>
<td>1%</td>
<td>1%</td>
</tr>
</tbody>
</table>

---

**Figure 1. Change of particle size distribution of pellets during the second test of emptying a pellet bin.**
coarse particles. The moisture content is low in all the samples, about 0.1%, and no change in bulk density can be seen when the particle size distribution is changed. Although only one of the pellet bins is at a low filling level, some effects on the process can be seen. In both tests, changed permeability, increased variation of heat load, decreased gas utilisation and variations in descent rate can be observed.

**Pilot scale test – charging of increased ratios of oversized pellets into the pilot blast furnace.**

The PBF has a diameter of 1.2m at tuyere level and a working volume of 8.2 m³. The height from tuyere to stock line is 6 m. The three tuyeres are located with a separation of 120°. In this test the furnace is equipped with a bell with fixed armour and operated with at top pressure of 0.85 bar overpressure and coal injection of approximately 100kg per tonne of hot metal.

The charging of pellets with an increased ratio of coarse pellets to the PBF is performed according to the experimental plan given in Table V. Three different fractions, 9-12.5mm, 12.5-16mm and +16mm, were obtained by screening MPBO normally charged into the blast furnaces at SSAB in Luleå. The experimental plan is adjusted during the test, because of difficulties in obtaining the correct screening analysis of the fraction 12.5-16 mm. The objectives were to verify that the process disturbances experienced at BF No 2 at SSAB are caused by the increased ratio of coarse pellets and to find out whether the disturbances can only be caused by the increased ratio of the fraction +16 or both fractions +16mm and 12.5-16mm.

The gas utilisation of the first period of testing, when pellets of the reference fraction are charged, varies as a result of some process disturbances, including a chilled hearth that was remedied just before the start of the test. The blast furnace performance deteriorates gradually, when the particle size distribution of charged pellets includes increased ratios of pellets of fraction 12.5-16mm and +16mm. The gas utilisation decreases and starts to vary more when pellets of particle size distribution 66/22/12 is charged. The burden descendent also becomes irregular and sometimes decreases to 2 cm/min, as compared to normal values of 4-5 cm/min for MPBO. Some small slips occur at the same time as EtaCO (gas utilisation) reaches minimum values of approximately 44. After the start of charging pellets of particle size distribution 33/37/30, the gas utilisation decreases further and starts to vary even more. The lowest value of EtaCO is 41.8 during this period. The blast furnace performance improves rapidly when pellets of particle size distribution 100/0/0 are charged into the PBF. The gas utilisation increases to an average of 50%. In Figure 2 the dumps of material and burden level during two shorter periods at the reference period with MPBO and the test with particle size distribution 33/37/30 are compared. When charging the pellets of particle size distribution 33/37/30 a couple of small slips occurred, as well as some periods with quite long intervals between the dumps.

### Table V. Original and adjusted experimental plan for test in the PBF. The figures correspond to the weight% of the fractions 9-12.5mm/12.5-16mm/+16 mm.

<table>
<thead>
<tr>
<th>Material</th>
<th>Planned particle size distribution</th>
<th>Real particle size distribution</th>
<th>Length of test, hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference of MPBO</td>
<td>72</td>
<td>28</td>
<td>0</td>
</tr>
<tr>
<td>Fraction No. 1</td>
<td>50</td>
<td>50</td>
<td>0</td>
</tr>
<tr>
<td>Fraction No. 2- Test 1</td>
<td>40</td>
<td>40</td>
<td>20</td>
</tr>
<tr>
<td>Test 2</td>
<td>40</td>
<td>40</td>
<td>20</td>
</tr>
<tr>
<td>Fraction No. 3</td>
<td>100</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Reference of MPBO</td>
<td>100</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

![Figure 2. Burden levels at two different periods of test.](image-url)
Table VI. Average of process data related to particle size distribution of charged pellets. *Data is based on data per hour except for EtaCO which is based on data per minute.*

<table>
<thead>
<tr>
<th>Particle size distribution 9-12.5/12.5-16/+16</th>
<th>EtaCO Average</th>
<th>EtaCO Std. deviation</th>
<th>Sol. Loss, Kg/thm Average</th>
<th>Sol. Loss, Std. deviation</th>
<th>pV bosh, Average</th>
<th>pV bosh, Std. deviation</th>
<th>Burden descendent cm/min</th>
<th>Burden descendent Std. deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>72/28/0</td>
<td>49</td>
<td>1.4</td>
<td>95</td>
<td>2.2</td>
<td>5.8</td>
<td>0.19</td>
<td>4.8</td>
<td>0.6</td>
</tr>
<tr>
<td>82/17/0</td>
<td>49</td>
<td>1.2</td>
<td>91</td>
<td>16</td>
<td>5.2</td>
<td>0.96</td>
<td>4.5</td>
<td>0.5</td>
</tr>
<tr>
<td>66/22/12</td>
<td>48</td>
<td>1.3</td>
<td>99</td>
<td>4.1</td>
<td>5.4</td>
<td>0.44</td>
<td>4.0</td>
<td>0.6</td>
</tr>
<tr>
<td>33/37/30</td>
<td>47</td>
<td>1.6</td>
<td>100</td>
<td>4.8</td>
<td>5.0</td>
<td>0.55</td>
<td>4.2</td>
<td>0.5</td>
</tr>
<tr>
<td>100/0/0</td>
<td>50</td>
<td>1.3</td>
<td>95</td>
<td>2.8</td>
<td>5.4</td>
<td>0.21</td>
<td>4.3</td>
<td>0.3</td>
</tr>
</tbody>
</table>

During the test period samples are taken with a shaft probe in the upper part of the shaft and with an inclined probe just above the cohesive zone. The samples are studied in an optical microscope and in a SEM. The samples from the upper shaft have very low reduction degrees and are composed mainly of magnetite and hematite. A difference between the core and the shell is noticeable, especially for the samples containing larger pellets, which also contain more cracks than the smaller pellets. The samples taken with the inclined probe, one of which is shown in Figure 3, are highly reduced and sharp borders between the cores and the shells can be seen by the naked eye. At this border between the metallic shell and the core, where there is a high content of wustite, a sintered band of metallic iron is found. The shell thickness is independent of pellet size and therefore the size of the core decreases with decreased pellet size. The core, especially in the larger pellets seemed to be on its way to entrain out from the pellets through the shell. Studies in a microscope and SEM show that the amount of metallic iron in the centre of the core is much higher in the smaller pellets than in the larger ones. This can be seen in Figure 4. MgO is dissolved in the iron oxide at low reduction degrees. At high reduction degrees, as in the shell part, MgO is found in the slag. The MgO content of the slag observed in the core between the iron oxide grains is less than 1% and the FeO content is ~20%. The MgO content of slag of approximately the same FeO content seems to increase when moving from the centre of the pellets towards the outer parts. The Fe content of the slag is high at low reduction degrees and decreases when the reduction degree increases. The MgO content observed in the wustite in the core of the coarse pellets is ~1.5% as compared to ~3-4% in the normal sized pellets.

**Laboratory tests**

**Properties of oxidised pellets** - The results from tumbler strength testing according to ISO 3271 and porosity measurements...
in mercury can be found in Table VII. Both the tumbler strength and the porosity are about the same for the fractions 9-12.5mm and 12.5-16mm but lower values are measured for the fraction +16mm. As can be seen in Figure 5, the distribution of pore size changes towards finer pores when the pellet size increases.

Study of the pellets in the optical microscope reveals that all pellet fractions are similar with respect to both core and shell structure. The cores are generally characterised by a high degree of sintering, but a low degree of oxidation, while the shells are characterised by a high degree of oxidation, but a low degree of sintering. The thickness of the shell is independent of pellet size; therefore the core increases with increased pellet diameter. The amount of residual magnetite can vary in the same fraction of pellets, too. Depending on the degree of oxidation, more or less residual magnetite is found. In these samples the amount of residual magnetite is higher in the pellets of fraction +16mm as compared to 12.5-16mm and 9-12.5mm. Pellets of fraction 9-12.5mm are almost fully oxidised. This is expected, as the oxidation starts at the pellet surface and proceeds topochemically. Thus, the time needed to complete the oxidation of the pellets depends on pellet size. In the centre of a large pellet the hematite often exists in limited areas, often in the form of lamellas. Partly reacted olivine grains can be found throughout the pellet. Close to these grains magnesium ferrite can be observed.

**Metallurgical properties -** Reduction properties of the pellets have been tested according to two different test procedures; one of them simulating the upper part of the shaft, where the pellets are reduced to 30% reduction degree; the other according to a blast furnace simulating test routine, where the pellets are reduced to 65% and 80% reduction degree, respectively. The pellets pre-reduced to a 30% reduction degree were tested in softening and melting tests in the blast furnace simulation model at MEFOS. The pellets pre-reduced to reduction degrees of 65% and 80%, respectively, were studied in the microscope, tested by tumbling and in softening and melting tests at the metallurgical laboratory (CK-lab) of LKAB, Malmberget.

**Reduction rate**

The pellets pre-reduced to wustite (30% reduction degree) are pre-heated to 400°C before a reduction gas consisting of 60%N₂/20%CO₂/15%CO/6% H₂ is introduced. Maximum reduction temperature of 900°C is reached after approximately 50 min. As can be seen from Table VIII, the time needed to achieve a 30% reduction degree increases when the particle size of the pellets increases. The achieved reduction degree after 60 minutes decreases with increased pellet size.

A blast-furnace-simulated reduction test is done to simulate the final reduction degrees of 65% and 80%, respectively. The changes in composition of reducing gas and reduction degree of pellets can be seen in Figure 6. The pellets of fraction 9-12.5mm first reach a ~30% reduction degree. At this point in the

<table>
<thead>
<tr>
<th>Fraction</th>
<th>Reduction time, min</th>
<th>Reduction degree, %</th>
<th>R₆₀%, %</th>
<th>Change of Pressure drop mm H₂O</th>
<th>Bed shrinkage %</th>
<th>Final reduction degree %</th>
<th>Reduction time, min</th>
</tr>
</thead>
<tbody>
<tr>
<td>9-12.5</td>
<td>60</td>
<td>20</td>
<td>0.5</td>
<td>3.15</td>
<td>15.3</td>
<td>80.1</td>
<td>207</td>
</tr>
<tr>
<td>12.5-16</td>
<td>95</td>
<td>19</td>
<td>0.5</td>
<td>3.05</td>
<td>13.5</td>
<td>80.2</td>
<td>215</td>
</tr>
<tr>
<td>+16</td>
<td>100</td>
<td>18</td>
<td>0.4</td>
<td>2.95</td>
<td>12.6</td>
<td>77.6</td>
<td>220</td>
</tr>
</tbody>
</table>

Table IX. Summarised results from blast furnace simulated reduction.
test the reducing gas is too weak to reduce the material further. Therefore, the two fractions containing larger pellets are allowed to catch up with the fraction of 9-12.5mm. The differences in reduction rate will therefore be less than maximum, but the result might still be representative of the blast furnace conditions. The summarised results from the reduction tests are found in Table IX. The reduction degrees after 60 min are 20%, 19% and 18% for the fractions 9-12.5mm, 12.5-16mm and +16mm, respectively. $R_{40}$ – the reduction rate at a 40% reduction degree of pellets – is only slightly lower for the fraction +16mm. Both the decrease in bed height and the pressure drop over the pellet bed are lowest for the fraction +16mm and highest for the fraction 9-12.5mm.

**Effect of reduction on disintegration and structure**

During the reduction to reduction degrees of 65% and 80% the pellets disintegrate and the disintegration increases, with increasing particle size of pellets. As can be seen from the photographs of the samples reduced to a 65% reduction degree in Figure 7 the cracking of the pellets increases, when the particle size of the pellets increases. The disintegration of both the oxidised and reduced pellets is also measured by a tumbling test. The results, which can be seen in Figure 8, show that although the tumbling strength and abrasion are approximately the same for all fractions before reduction, they will decrease and increase more, respectively, when the pellet size increases. This means that the larger pellets more easily generate fines both by cracking and abrasion. After tumbling a lot of naked cores, from which the shells have fallen off, are found in the samples of pellets of fractions 12.5-16 and +16mm.

Reduction of the pellets is also done in a swelling test, in which eighteen pellets were reduced to 80% reduction degree at 1000°C in a reducing gas consisting of 60%N₂/40%CO. The swelling is estimated from volume measurement in mercury and average diameter is measured by measuring the total length of the row of pellets with an inclined ruler. As can be seen in Figure 9, the swelling increases, when the particle size of pellets increases. The lower swelling estimated by volume measurements in mercury is explained by the formation of large cracks, into which the mercury can entrain.

The different fractions of pellets reduced to a reduction degree of 65% were studied by chemical analyses and by optical
microscope. As expected the chemical analyses of the material from the cores and the shells of the different fractions indicate a much higher FeO content and a lower Fe$_{\text{met}}$ content in the cores as compared to those of the shells. A comparison of the content of Fe$_{\text{met}}$ and FeO in cores and shells of different fractions can be seen in Figure 10. The shells are well reduced and the shells of pellets of larger diameter contain even more Fe$_{\text{met}}$ as compared to the pellets of fraction 9-12.5mm. This can be explained by the fact that the reduction time increases with increased pellet diameter. Studies in the optical microscope indicate the same applies with respect to the reduction degree in both the shell and core. The shell is of about the same thickness independent of the pellet diameter. The diameter of the core increases with increased pellet diameter. The shells are generally well reduced, but the amount of Fe$_{\text{met}}$ decreases slightly when comparing the outer part of the shell with the inner part of it. The amount of Fe$_{\text{met}}$ decreases on the way into the centre of the pellets. In the largest pellets almost no metallic iron is found in the centre. In Figure 11 the changes in structure when moving from the surface into the centre of a 16mm diameter pellet in are shown.

![Figure 11. The structure of a pellet of fraction +16mm reduced to 65% reduction degree. The photos of the pellet are taken in the optical microscope at the periphery, 1.5 shell thickness inside the shell and in the centre of the core, respectively. (a = gangue, b = pore, c = wustite, d = Fe$_{\text{met}}$.)](image)

**Softening and melting behaviour**

The softening and melting properties of pellets pre-reduced to 30% reduction degree are evaluated under blast-furnace-simulated conditions using the MEFOS blast furnace model. The samples of a total weight of ~ 640g consist of pellets pre-reduced to approximately 30% reduction degree with 7% BOF slag evenly distributed in the pellet bed. BOF slag is added to get approximately the same basicity as in the blast furnace burden. The sample is sandwiched between coke layers in a graphite crucible with a diameter of 80 mm. A load of 49 kPa is applied and a total gas flow of 270 l/min is introduced. The gas consists of 100% N$_2$ up to 900°C and after that of 61%N$_2$, 35%CO and 4%H$_2$. Several data are logged during the test; among them temperature, shrinkage of bed and the pressure drop over the bed. Both full tests up to dripping, at the point when the bed stops shrinking, and tests interrupted at approximately 1450°C, just before pressure drop starts to increase rapidly and the melting starts, are performed. The softening temperature is defined as the temperature at which the shrinkage of the bed is 50% (T$_{50\%}$). The melt out temperature is defined as the temperature at which the maximum pressure drop is registered (T$_{\text{Tpmax}}$). The height of the cohesive zone is defined as the interval from the start of softening until the bed stops shrinking (T$_{\text{(end of shrinkage)}}$- T$_{50\%}$). As can be seen in Table X, the melt out temperature, as well as the height of the cohesive zone increases with increased pellet diameter. The height of the cohesive zone is increased as a result of a decreased softening temperature, an increased melt out temperature and an increased temperature at the stop of bed shrinkage. The pressure drop around 1300°C increased with the increased pellet diameter, but the pressure drop at melt down decreased with the increased pellet diameter. Chemical
composition of the dripping metal is found in Table XI. The chemical energy – the amount of C, Si and Mn dissolved in the dripped metal – of the dripped metal decreases when the pellet diameter increases.

The quenched material from the interrupted test shown in Figure 12 indicates residual iron oxide in some cores in the sample containing pellets of fraction +16mm. Studies of samples of fractions 9-12.5mm and +16mm from interrupted tests in an optical microscope and by SEM indicate higher amounts of residual oxygen and considerably higher amounts of iron oxide containing slag in the sample of fraction +16mm as compared to those in the sample of fraction 9-12.5mm. One image from each fraction showing the difference in slag content, is found in Figure 13.

Softening and melting tests in N₂ atmosphere are performed on pellets of the three fractions pre-reduced to 65% and 80% reduction degrees. Also in these tests, 7% BOF slag is added to the bed and the sample is sandwiched between coke layers in a graphite crucible measuring 40mm in diameter. The tests show that the softening and melting temperatures increase with increased reduction degree. The softening and melting temperatures are comparable for the fractions 9-12.5mm and 12.5-16mm, but lower for the fraction +16mm. The dripping starts approximately 35°C earlier for the fraction +16mm as compared to 9-12.5mm and 12.5-16mm for both the 65% and 80% reduction degrees. No significant difference related to the fractions is found for the temperatures at stop of shrinkage or stop of dripping.

**DISCUSSION**

**Structure of the pellets**

There is heterogeneity of structure in the pellets – meaning that the structure of the core differs from that of the shell – for both oxidised and reduced pellets. The same pellet structure is found in all fractions, but the volume of the core structure increases with increased pellet diameter. For the oxidised pellets, the amount of residual magnetite in the centre increases with increased pellet diameter. In the reduced pellets the amount of wustite is much higher in the centre as compared to the shell. The heterogeneity of structure is similar for pellets reduced to both 65% and 80% reduction degrees but even more pronounced for the latter. The amount of
metallic iron in the centre of the reduced pellet decreases, while the FeO content increases with increased pellet diameter.

**Permeability**

When charging higher ratios of fraction +16 and 12.5-16mm increased variations in permeability over the blast furnace have often been experienced. An increase in permeability can be seen at the start of charging of increased ratios of oversized pellets, and period of high and low permeability recur during the periods when a high portion of coarse pellets is charged into the blast furnace. Together with the variations in permeability, also decreased and more varied gas efficiency and greatly varied burden movements occur. The phenomena affecting the permeability of the blast furnace burden will also change the gas distribution in the blast furnace. When operating with high rates of coal injection the amount of coke is greatly decreased. The phenomena changing the permeability will therefore have large impact on the blast furnace process. When operating the blast furnace with a greater amount of coke and less coal injection the coke layers will stabilise the gas distribution to a greater extent and the effect of the coarse pellets on the blast furnace process will be minimised.

**The effect of disintegration** – The disintegration of pellets during reduction increases with increased pellet diameter. At tumbling after reduction disintegration increases with increased pellet diameter. Further the swelling tests show increased crack formation and swelling with increased particle size. This means that even if the original reason for disturbance in the blast furnace process was not the charging of pellet fines into the blast furnace at low filling levels of pellet bins, the process disturbance might still be caused by secondarily formed fines. The process disturbances in the blast furnace might be partly due to the formation of large amount of fines inside the blast furnace as a result of disintegration of the oversized pellets during reduction. The typical symptoms of fines in the blast furnace are irregular burden descent and variations in gas utilisation, caused by inactive zones in the blast furnace, which disturb the gas distribution.

**The effect of softening and melting properties** – The three pellet fractions studied differ in softening and melting performance. At softening, the bed shrinkage and pressure drop increases with an increased pellet size. The temperature interval of the estimated cohesive zone increases with increased pellet size. This may partly explain the periods of increased pressure drop when the blast furnace is charged with increased ratios of coarse pellets.

The pellets taken from the PBF with the inclined probe contains wustite with some MgO. Both core size and FeO content increases with increased pellet size. The MgO in the wustite will increase the melting point of the wustite phase[5][7], but the MgO content of the wustite phase is much lower in the coarse pellets than in the normal sized ones. When magnesiowusite is further reduced the MgO is dissolved in the slag phase and increases the liquidus temperature of the slag, which initially contains considerable amounts of FeO [5][7]. In the cores of all the pellets studied the slag contains less than 1% MgO but up to 4+% CaO. The melting point of this slag low in MgO content varies depending on the chemical composition, and especially on the FeO content, as in the area shown in the phase-diagram in Figure 14. The area drawn is based on normalised

![Figure 14. The CaO-FeO-MgO system](image)
values of the main chemical components of the slag phase. High amounts of wustite with low concentrations of MgO as well as high amounts of early melting slag may cause lower softening temperature and therefore larger deformation of the pellets. The core can also more easily entrain out through the pellet shell if the amount of liquid material formed is high. In the softening and melting test for the coarsest fraction the first rapid increase in pressure drop, usually corresponding to the first slag melting, takes place at the lowest temperature.

The temperature interval for the estimated cohesive zone will increase with increased pellet diameter both as a result of lower softening temperature for the reasons explained and as a result of the higher melting temperature of the metallic iron. The chemical analysis of hot metal and of dripping material in laboratory tests indicates that the melting temperature is increased as a result of lower content of C and Si.

Gas utilisation — The effect of reduction rate.

The decreased gas utilisation observed when larger amount of coarse pellets were charged into BF No 2 at SSAB in Luleå and in pilot scale tests in the LKAB PBF is a symptom of the decreased reduction rate of the coarse pellets. One reason is, of course, that the lower surface to volume ratio results in longer distance for the diffusion of reducing gas. The microscopic study of samples taken by the inclined probe indicates that the gases penetrate the same distance into the pellets, independent of pellet size. Another important reason is the large core part of the coarse oxidised pellets that contains higher amounts of magnetite, which has negative impact on reduction for several reasons. The reaction rate of reduction from primary magnetite is lower than that of reduction of hematite. The porosity of the magnetite itself, as well as the wustite formed at reduction of magnetite, is lower as compared to hematite and secondary magnetite, which has high micro porosity and produces a porous wustite at reduction \[6\] \[7\]. The decreased gas utilisation will result in an increased direct reduction rate further down in the blast furnace. This means that the energy consumption increases and the carbonisation of hot metal will be delayed. The hot metal from BF No 2, as well as the dripped metal in the blast furnace simulation test at MEFOS, has a significantly decreased heat level in terms of lower C, Si and Mn contents when pellets of fractions 12.5-16mm and +16mm are charged as compared to 9-12.5mm pellets. At BF No 2 decreased hot metal temperature is also experienced when charging coarser fractions of pellets.

Control of charging

The results of full-scale tests in which an increased amount of coarse pellets was charged into the blast furnace when levels in pellets bins were low, together with the knowledge gained from the study of the effect of this on the process, have resulted in considerably improvements in the particle size distribution of the pellets. In the material delivered by LKAB the ratio of 9-12.5mm pellets has increased and is much more stable. At SSAB Luleå the personnel working with the control of the levels in silos and bins keep the levels high enough to avoid charging of the coarse material in the BF. If for some reason, for example, a belt conveyer is damaged, the particle size distribution of the pellets changes, the personnel in charge of the control of the process know how to minimise the effects. The effects of the charged coarse pellets are greatly reduced by operating the blast furnace at higher coke rate, a lower coal injection rate and slightly higher fuel rates than normal. If these precautions are taken, the adverse effects of coarse pellets on the blast furnace process will be greatly reduced.

CONCLUSIONS

The negative effect of coarse pellets on the blast furnace process has been verified both in full-scale tests, pilot-scale tests and laboratory tests. It has been concluded that the negative effect on the BF process was resulted from a decreased reduction rate, reduced pellet strength during reduction, an increased swelling and an increased temperature interval of cohesive zone with increased pellets size.

In practice, the charging of pellet material containing excessive amounts of coarse pellets can be largely avoided through co-operation with the pellet supplier and through effective control of pellets silos and bins by the responsible personnel.
If charging of excessive amounts of coarse pellets cannot be avoided, the negative effect high of ratios of coarse pellets in the pellets charged into the blast furnace can be effectively counter-acted by charging increased amounts of coke, and decreasing the coal injection rate and increasing the total fuel rate.

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This work is based on experiences from industrial blast furnaces.

1. Process irregularities when testing self-fluxed pellets. 2. Process disturbances when charging increased proportions of coarse pellets

Laboratory tests to evaluate the effect of basic fluxes on the slag formation in the bosh and in the raceway have been carried out. Pilot scale tests have been performed to verify the effect of coarse pellets. The effect of reduction degree and the reduction behaviour on the slag formation and blast furnace performance have been evaluated

It was found that decreased degree of reduction of pellets or lowly reduced core of coarse pellets decrease the melting temperature and increase the softening and melting temperature interval. Basic fluxes have a negative effect on the melting properties of the self-fluxed pellets and a positive effect on the melting properties of the olivine pellets. Basic fluxes have a positive effect on the melting properties of tuyere slags.