GRANULATION OF FERROALLOYS
AND Si-METAL

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ABSTRACT
Granulation of liquid metal offers a simple technique for solidification of metals to customer friendly products. However the pouring of liquid metal into water has always been regarded as hazardous. Several plants for granulation of steel and different kinds of ferroalloys show that granulation can be made in a safe and reliable way. The granulation of ferrosilicon and especially silicon metal offer certain problems. Granulation of these metals at high flow rates have resulted in a risk of explosions. The explosions are considered to be due to a too high power generation and thereby a rapid formation of steam. By using a one dimensional spherical model the heat transfer rate has been calculated. It is anticipated that the granules are surrounded by a stable vapor film above a certain temperature. Below that temperature and down to about 100°C the heat transfer is conducted by boiling bubbles which leave the face boundary with the result of an increase of the heat transfer coefficient. Below 100°C of the granule the face boundary consists of a static water layer and the heat transfer coefficient is again decreased.

The power generation per volume unit is a function of the heat transfer rate and the falling velocity of the granules. Light metals like ferrosilicon and silicon-metal have a comparatively low falling velocity in the water. This will result in a high power generation per water volume unit. To decrease the power concentration the heated water has to be efficiently replaced or the heat has to be distributed to a big volume. It has been found that the replacement of the water in a small cooling zone in a big water tank is rather difficult but that the metal can be efficiently distributed over a big water surface to decrease the power concentration.

1. INTRODUCTION
Solidification of ferroalloys and similar types of intermediate products is done in many different ways. The special demands connected to these type of materials have to be carefully considered when a solidification method is selected or developed. At least the following parameters are of interest:
- The tendency to segregate
- The final shape

- The yield
- The production cost

These parameters can be contradictory in some cases but could also coincide in best cases. The ways developed for solidification and final shaping of the material are based on the characteristics of the different type of materials.

<table>
<thead>
<tr>
<th>CHARACTERISTIC (example)</th>
<th>TYPE OF MATERIAL (example)</th>
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</thead>
<tbody>
<tr>
<td>Extremely hard</td>
<td>FeCr MC</td>
</tr>
<tr>
<td>Ductile</td>
<td>FeNi, Ni, Steel (iron), Al</td>
</tr>
<tr>
<td>Creates fines when crushed</td>
<td>FeCr HC, FeSi, Si, SiMn etc.</td>
</tr>
<tr>
<td>Segregates</td>
<td>FeCr, FeSi, FeMn, SiMn etc.</td>
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Casting in sand beds in thin layers or casting in moulds with subsequent crushing and screening are the dominating methods today to solidity and shape ferroalloys. For ductile material casting to final products in small moulds is common.

It is a trend that the customers—steel and chemical plants—are looking for smaller pieces to allow automated handling. Also faster dissolution or faster reactions are desired by the users.

The new trend has paved the way for granulation of the liquid metals as a solidifying technique. Although many different granulation methods based on water quenching have been developed there seem to be a reluctance among many producers to adopt these methods, as they regard it hazardous with risk of explosions when liquid metal is poured into water. This is especially true for the producers of FeSi and Si-metal.

In this paper the granulation in water is discussed mainly from heat evolution and heat transfer point of view. An attempt is made to define safe conditions for granulation. The actual mechanisms for explosions are however not penetrated.

2. GRANULATION METHODS
Except for granulation of slags, there is—in the author's knowledge—no industrial granulation method for iron, steel or ferroalloys, which is not based on water quenching.

Typical methods are:
- a stream of liquid metal is split up with high pressure water jets
- pouring directly into water
- breaking up of a metal stream against an impact element.

Slags are often granulated in high pressure water jets. This category also includes methods for making blasting shots.
One, two or more streams of molten metal impinge upon high pressure annular sprays of water whereby the metal is caused to disintegrate into particles and the particles drop down into a watertank underneath. The water pressure and thereby the velocity of the water determine the size of the granules formed.

Figure 2 illustrates an early method of making iron shots by pouring directly into water. A screen is placed just below the water surface.

The Granshot method of which method the authors have most experience falls under the third category where the stream of molten metal is split up against a refractory target. The impact energy in the molten metal stream breaks up the metal in an umbrella-shaped spreading.

The size distribution of the granulated product is given mainly by the energy in the stream of molten metal. Simply speaking, low energy in the stream gives bigger granules, high energy content gives smaller granules. The surface tension of the metal plays also an important role.

Over the years, more or less imaginative granulation methods have been developed. Whether the apparatus illustrated in figure 4 find any industrial use is not known to the authors.

3. EXPLOSIONS CONNECTED TO GRANULATION

Most people in the metal producing industry have some experience of explosions connected to liquid metal and water. In most cases the explosions arise from a situation where a large quantity of liquid metal is poured on top of a small amount of water or ice or on top of a wet surface.
In all granulation processes relatively small amounts of metal is poured into a large amount of water. This does not normally create any problem. However occasionally there may be an explosion in a granulation system. The mechanisms for explosions seems not to be fully understood but the following reasons are often discussed:

- Generation and expansion of steam at an explosive rate
- Generation of hydrogen at an explosive rate
- Generation of hydrogen which reacts with oxygen (oxy-hydrogen gas).

While the first two types of explosion mechanisms occur in the water, the reaction between hydrogen and oxygen may occur in the atmosphere above the water surface. Both types of explosions are serious and have to be avoided.

4. HYDROGEN GENERATION

During granulation the metal will react with the water and form hydrogen according to the following reaction:

\[ X \text{Me} + Y \text{H}_2\text{O} \rightarrow \text{MeXO}_Y + Y \text{H}_2 \]

The hydrogen formation can be observed visually during granulation by the characteristic "hydrogen flame" when it is lit by the hot metal and combusted above the water surface. The amount of hydrogen formed is not measured quantitatively but it is obvious from visual observations that the amount increases with increasing flow rate of the metal.

Water or steam can be reduced from all the metals which are of interest to granulate. The driving force for the reduction is of course largest for the metals with the highest oxygen affinity. Here FeSi and Si-metals are of special interest.

If the hydrogen is lit directly above the water surface it will not create any risk for an explosion. If the hydrogen however is trapped in pockets in the plant construction it may form hydro-oxygen gas and become a serious explosion risk.

The oxidation of 1 kg Si corresponds to 1.6 Nm³ H₂ while an oxygen content of 100 ppm only corresponds to 0.004 Nm³ H₂ per ton silicon.

The amount of SiO₂ which is generated during full scale granulation has not been measured exactly. However from visual observations of silica in the system after granulation it is estimated that a maximum of 0.5 % Si is oxidised during the particles path through the water. This would correspond to a hydrogen evolution of 0.08 Nm³ per second at a granulation rate of 600 kg Si per minute.

It is obvious that the limited hydrogen generation cannot cause any explosion by itself in a large water system.

5. HEAT GENERATION IN A GRANULATION SYSTEM

In most granulation systems the metal is split up in the air and falls down into water where the metal is quenched. A complete heat balance should involve the heat transfer from the metal to the air during the metal droplets trajectory before it hits the water and the heat transfer from the metal to the water. It should also involve heat of reaction.

In the following the heat transfer metal-to-air and metal-to-water and the heat of reaction from metal oxidation in the water is discussed. Granulation of Si-metal, FeSi (75% Si) and pure Fe is compared. For FeSi the properties for the pure elements have been used in proportion to the composition. It is assumed that the temperature at the start of the granulation is about 100 °C above the liquidus temperature.
5.2. Heat transfer in the water

To calculate the heat transfer rate a one dimensional spherical model has been used.

Even in cases when water is injected at high flow rates (5–30 m³/minute) and the falling particles interact with each other and local boiling occurs, it is assumed that it is reasonable to use a simple model where the heat transfer rate from the metal particle to the water is not affected by the water movement.

During the initial part of the solidification when the temperature is high a stable vapor-film surrounds each particle. The heat transfer rate is controlled by the diffusion of heat through the vapour layer. When the temperature decreases the vapour film is broken up and the heat transfer is conducted by steam bubbles which leave the face boundary and the heat transfer coefficient is increased. Below 100°C of the particle the face boundary consists of a static water layer and the heat transfer coefficient is decreased again.

The model for the heat transfer has been solved numerically. The result is plotted in figures 9 and 10 for Si-metal and in figures 11 and 12 for Fe. The generated power is different for different particle sizes depending on a different area/volume ratio which means that small particles leave their heat quicker and therefore generate a higher power. The total transferred energy per weight unit is of course the same irrespectively of the particle size.

The time has been transferred to a falling depth in a water tank by using the falling velocity for the compared metals. The falling velocities have been measured in a water colon.
Metal    Falling velocity
Si-metal  0.37 m/sec
FeSi      0.49 m/sec
Iron      0.85 m/sec

In reality the velocity will be slightly different depending on the water flow pattern. In the case that most of the water is discharged through the bottom of the tank the velocity will be a little higher. This is however not considered to have any considerable effect on the result.

Figure 9. Power generation for different particle size; 2–5 mm; Si-metal.

Figure 10. Power generation for different particle size; 18–35 mm; Si-metal.

Figure 11. Power generation for different particle size; 2–12 mm; Fe.

Figure 12. Power generation for different particle size; 15–35 mm; Fe.

For silicon the estimated time for when a liquid phase is present in each particle is marked by the coarse part of the line. While particles with a diameter of less than 8 mm are completely solidified after a path in the water corresponding to a depth of less than 3 meters, particles with diameters of 35 mm are not completely solid before they reach a depth of 10 meters.

With known size distribution and known falling velocity of the particles the total generated power from each particle can be integrated over a certain depth in the tank.

In figure 13 the power generation has been integrated over the time elapsed for the particles to fall 0–1 meter, 1–2 meter etc., which gives the energy that is generated at different levels in the tank. Typical size distributions have been used.
At a given granulation rate and size distribution the total power to the system is given. To keep the power concentration in the system low it is necessary to either add water to the zone where the power is generated and/or to spread out the metal over a large water surface and thereby increase the zone.

To be able to dilute the heat concentration by injection of water the injected water has to penetrate and replace the heated water. In a large water tank this is difficult to achieve when the metal and hence the heat is distributed to a small part of the water. In figure 14 the temperature increase of a heated zone of 3 m² in a water tank containing 100 m³ of water is plotted as a function of the percentage of the total water which is replaced. To the heated zone liquid silicon is added at a rate of 500 kg per minute. It is assumed that the replacement rate of water is the same in all parts of the total system.

It can be seen from figure 14 that more than 2% of the total water has to be replaced every second to keep a constant temperature below 100°C in the heated zone. This corresponds to more than 120 m³ of water in this specific system. By directing the water injection towards the heated zone the necessary amount of water will be less. However this is a difficult task in a large water system.

If the heated zone is made larger the power concentration will be lower and hence the necessary amount of water will be less to achieve the same cooling effect. In the case of silicon granulation and when relatively small particles are produced the slow falling velocity makes it necessary to distribute the metal over a large surface since most of the heat transfer will take place in the upper region of the tank.

A way of distributing the metal in a controlled way over a large water surface can be achieved by pouring the metal in the form of a stream against an impact element placed in the centre of a cylindrical water tank. By oscillating the impact element vertically up and down in a controlled manner the metal will continuously vary the radius of the annular region within which the majority of the drops hit the water. The spreading is controlled by the height of the metal surface above the impact element, the distance between the impact element...
and the water, the amplitude and frequency of the oscillating movement, the acceleration and the maximum velocity of the impact element. In comparison with a stationary or a rotating impact element where the metal enter the water at a fixed annular region the power concentration can be reduced by a factor 5 in a tank with a radius of 3 meter.

Figure 15 shows typical parameters and figure 16 shows how the metal is distributed over the surface.

Figure 15. Typical parameters for an oscillating impact target.

$r1$ = annular spreading of metal
$v1$ = velocity of impact element
$h1$ = height of impact element

Figure 16. Metal distribution using the parameters shown in figure 15.

7. CONCLUSION
The exact mechanism which triggers explosions in granulation systems is not known. However it is concluded that explosions can occur if a critical power generation per volume unit is generated.

The power generation per volume unit “power concentration” is a function of the heat transfer rate and the falling velocity of the granules. Light metals like ferrosilicon and silicon-metal have a comparatively low falling velocity in the water and a high heat content. This results in a high power concentration. To decrease the power concentration the heated water has to be efficiently replaced or the heat has to be distributed to a large volume. It has been found that replacement of the water in a small heated zone which is penetrate by the metal in a large water tank is rather difficult but that the metal can be efficiently distributed over a large water surface to decrease the power concentration.

By an efficient distribution of the liquid metal in a granulation tank of industrial size the power concentration can be reduced with a factor 5. Considering that granulation rates of more than 2 tons a minute for iron, steel, FeNi, FeCr and granulation rates of 500 kg a minute for silicon-metal is achieved in production plants where the metal is distributed to a small fixed annular region, there is a great potential to increase the granulation rates.

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