Real-time Meniscus Level and Slag Thickness Measurement by RADAR

Part II: Results on Liquid Steel and Melting Mould Powder

Frenk van den Berg and Haibing Yang
Tata Steel Research, Development and Technology, 1970 CA, IJmuiden, The Netherlands

ABSTRACT

In part I of the paper [1], an ultra-wideband RADAR system has been described which serves as prototype for highly resolution studies in monitoring slag thickness and meniscus level in a continuous cast system. In he second part here, results of trials on liquid steel confirming the fine resolution capability of the system are presented, as well as data on the evolution of the slag thickness in time during heating.

Introduction

In part I of this paper [1], the motivation to investigate RADAR as highly potential technology for monitoring the stability of the meniscus level and the local thickness of the mould powder/slag layer, has been presented in detail. The same paper has also explained the system design and its characteristics and described the steps in the data processing which are required to enhance the signal-to-background ratio needed for proper separation of the reflections from the mould powder and the meniscus. The present paper, which is Part II of a series of two papers, highlights the results from trials on liquid steel and data on the evolution of the slag thickness in time during heating. In section 2, the experimental conditions for these trials are given. The results of the trials are described in section 3.

Experimental method

To assess the technology for liquid steel level monitoring, steel has been melted in an induction furnace. Figure 1 shows the setup in operation. Due to induction, the steel meniscus has a dome shape in the furnace pot; hence, for reference measurements, the induction heating has been temporarily switched off.

Since a stable reference level of liquid steel cannot be prolonged over the duration of the melting process of the flux powder, and because under these conditions a large temperature gradient over the flux powder/slag layer would be present, a different setup is configured for the establishment of the microwave dielectric properties of the flux powder/slag as a function of the temperature. For this experiment, a stainless steel pot, filled with mould powder layer of uniform thickness, is slowly heated in a radiation furnace, while the radar levels of mould powder and pot bottom are monitored with time.

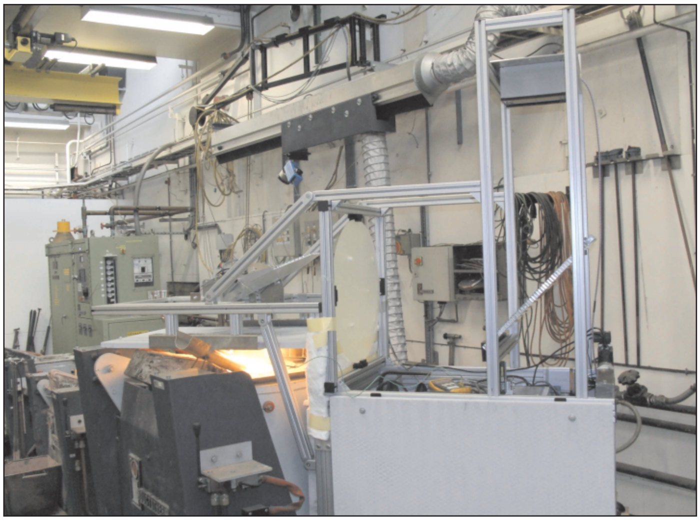

Fig. 1: Radar system measuring above liquid steel in induction furnace in a laboratory trial.

Results

Distance accuracy and linearity

To assess the accuracy and linearity of the ultra-wideband RADAR technique, a leaky lens antenna has been separately tested on a single metal target. In this particular test-setup, the distance between RADAR and target was short, only 25 cm at maximum. Figure 2 compares the distance deduced from the RADAR signal with the manually measured distance using a ruler. The data indicates a distance resolution of about 1 mm, over a range of (more than) 15 cm; as expected, a linear relation is obtained.

Results on liquid steel

Figure 3 shows the results obtained on liquid steel. The red solid line represents the temperature of the liquid steel, corresponding with the second y-axis on the right. The vertical positions of the dots indicate the meniscus level as measured by the radar. The colour of the data point denotes the relative strength of the radar signal. At time 13:48, the induction power is set to the maximum of 200kW. At this point, the steel meniscus immediately jumps to a higher level because of the dome shape of the bath imposed by the Lorentz forces. Next, the (average) level steadily increases due to thermal expansion.

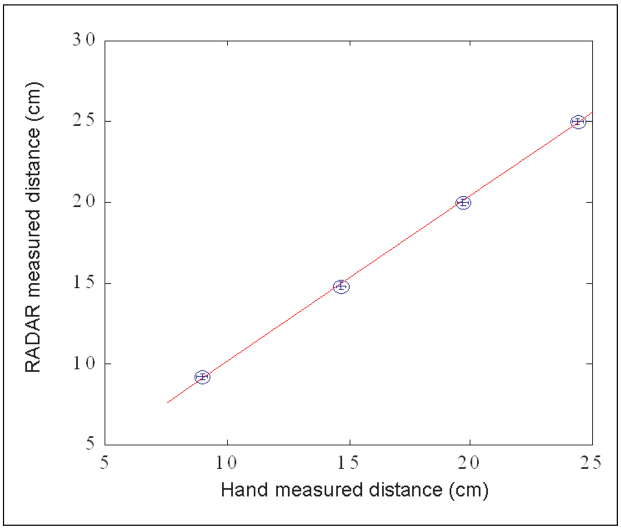

Fig. 2: Radar measured distance versus reference position over a range of 15 cm.

Due to the electromagnetic stirring effect, the liquid steel bath becomes agitated as seen by the scatter of the data points. After switching off of the power, at time = 13:51, the dome shape due to the Lorentz forces disappears instantaneously, and after damping of the meniscus fluctuations, the bath becomes very stable. The meniscus level slowly decreases in time because of thermal contraction due to the cooling of the liquid steel. As evidenced by Figure 3, the measurement is here very stable, with a statistical error well below 1 mm. The deep red colour of the data points indicates the strong signal reflection on liquid steel. Due to thermal gradients, the level does not exactly keep up with the (locally measured) temperature.

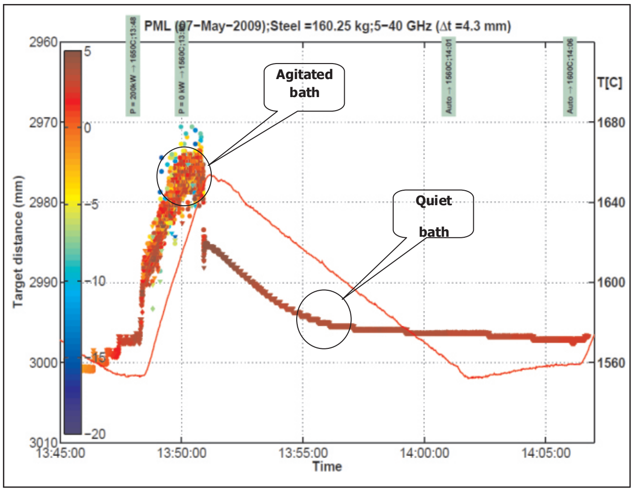

Fig. 3: Radar trial on bare steel

Results on melting mould powder

To study the temperature dependence of the RADAR dielectric properties of mould powder, the RADAR system was positioned above a stainless steel pot filled with a uniform layer of mould powder. The pot, equipped with K-type thermocouples, was heated in a radiation furnace in steps of 100°C up to almost 1300°C. The radiation furnace was covered with a calcium silicate plate, 25 mm thick, acting both as furnace lid to obtain a (relatively) uniform temperature inside the oven, and as radiation shield to protect the radar system from the heat radiation from the furnace and measurement target.

Figure 4 shows a distance spectrum obtained by the system, zoomed-in around the target, at room temperature: the different curves display the raw signal, the signal after background subtraction and the signal after de-convolution. Note that the y-scale is logarithmic, and note the efficiency of the de-convolution algorithm which improves the signal-to-background ratio by about 10 - 20 dB, i.e. a factor 10 - 100.

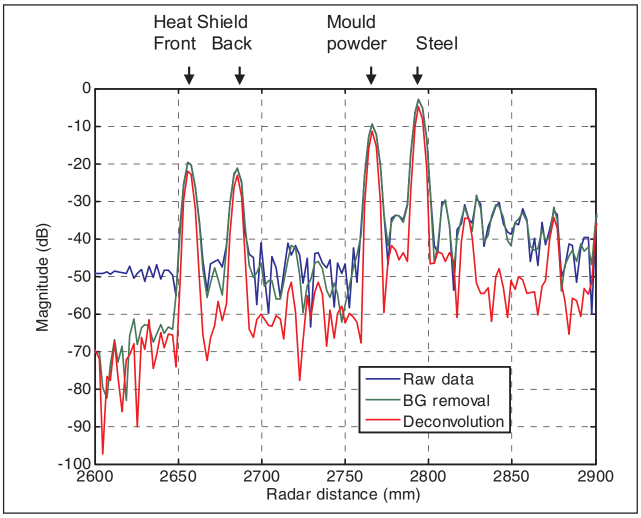

Fig. 4: Close up of the distance spectrum of the radar trial on mould powder on steel

The first two peaks in the spectrum correspond with the upper and bottom side of the calcium silicate heat shield. The electrical distance, i.e. the distance between the peaks is about 32 mm. Since the geometrical thickness of the heat shield is 25 mm, it is readily deduced that the refractive index of the heat shield material is around 1.3.

In a similar way, the refractive index of the mould powder can be deduced from the distance between the peaks from the interface air-mould powder (the 3rd peak) and the interface mould powder - steel (the 4th peak). Whereas the geometrical thickness of the mould powder layer is 19.5 mm, the electrical distance measured by the radar is 28 mm, corresponding with a refractive index of the mould powder of 1.43.

The above results demonstrate the importance of knowledge of the refractive index of the mould powder, not only at room temperature, but also at elevated temperatures. From physics reasons, it may be expected that the refractive index is not constant over density, since the mould powder shrinks during temperature increase, hence its density increases. Subsequently it melts around 1050 °C to form liquid slag. Electrical polarisation in liquids tends to differ from solid state polarisation.

The measured geometrical thickness and the electrical thickness during heating of the mould powder are depicted in Figure 5. The geometrical thickness is deduced from the position of the air-mould powder peak (the "third peak" in Figure 4) and the fact that the bottom of the steel pot is at constant position during the experiment. The electrical distance is deduced from the distance between the 3rd and 4th peak (Figure 4). Remarkable is the phenomenon taking place at T = 800-1000°C, where the physical thickness decreases dramatically by a factor ~2.5, while the electrical distance stays constant. We interpret this phenomenon to the compactification of the mould powder, where the resulting higher density causes the electrical thickness to remain constant. Around T = 1050 °C, the electrical distance drops by a factor of almost 2. Also, we observe here a further increase of the density of the layer. We attribute this to the melting of the (compacted) mould powder layer.

During subsequent temperature fluctuations in the range T = 1000 - 1300 °C, the electrical thickness remains (almost) constant. Note the strong change in thickness over the entire temperature trajectory: from about 20 mm initially to around 3mm in the liquid state. The data in Figure 5 suggests that solidification of the liquid slag is accompanied by a little volume expansion.

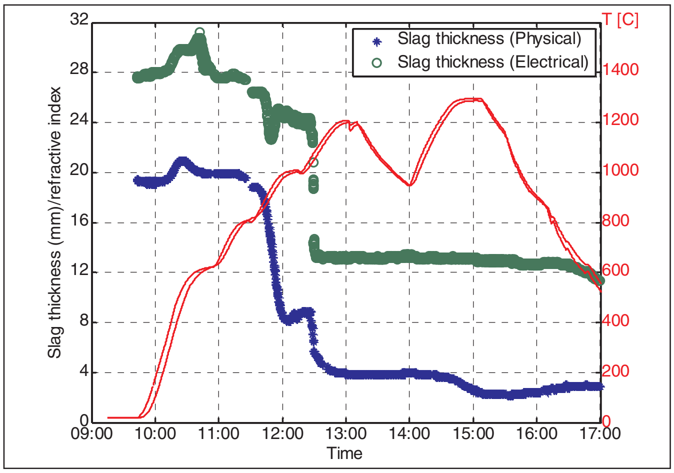

Fig. 6: Refractive index of mould powder and mould slag as function of the temperature, as deduced from the data in Figure 5

The ratio of the electrical thickness and geometrical thickness equals the refractive index, and this factor has been plotted as a function of the temperature in Figure 6. The data indicate a stable refractive index in the temperature range 20-900°C, except for some small but clearly visible

(Figure 5) deviation around T = 600°C, which is attributed to the evaporation of some substances out of the mould powder.

From 900°C onwards, the refractive index rapidly grows to a value of 3.0 +/- 0.2, caused by the aforementioned compactification and softening. The melting of the powder around T = 1050°C causes the refractive index to jump to a value of 4 for the liquid slag. Further temperature rise of the liquid slag results in an approximately linear increase in refractive index with a slope of about 0.7 per 100°C.

Discussion

Implication of the results for slag layer thickness monitoring with radar

The results from Figure 5 and Figure 6 yield the essential data that is needed to convert the electrical thickness (ET) measured by the radar to the physical thickness (PT) of the mould powder/slag layer in the application of process monitoring during continuous casting, since these entities are linked by:

$$ET = \int_0^{PT} n(z)\cdot dz = \int_0^{PT} n(T(z))\cdot dz \qquad (1)$$

where the function n(T) is refractive index over temperature and T(z) is temperature over powder/slag layer depth z.

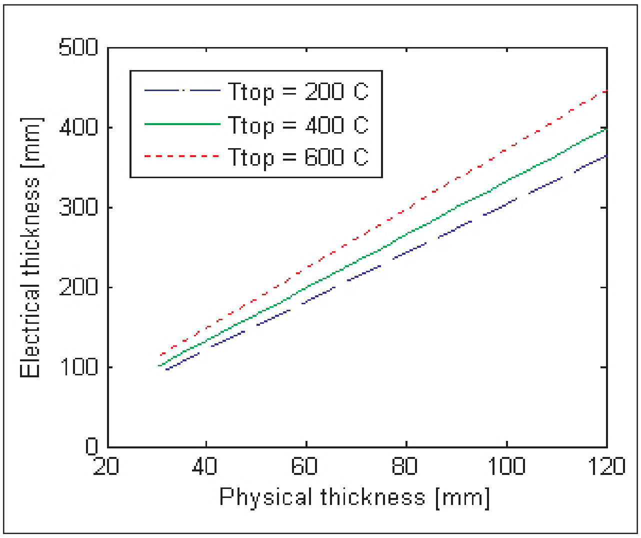

Figure 7: Electrical thickness (by RADAR) versus physical (geometrical) thickness, for three different top surface temperatures of the mould powder.

In a first approximation, we assumed a linear temperature gradient through the powder/slag layer thickness, which is justified by the measurements reported in [2]. By evaluating the integral of equation 1 for a series of thicknesses in the practically applied range, Figure 7 is obtained. The relation has been evaluated for 3 different temperatures of the mould powder surface. For accurate thickness monitoring, the graph evidences that the top surface temperature has to be taken into account, which can be realised in practice by simultaneous temperature measurement using a pyrometer of infrared camera.

Still, the sensitivity of the thickness measurement to top surface temperature is relatively low, i.e. 10% for a 200 °C temperature shift. Hence, when continuous supply of mould powder is supplied, the top temperature will be relatively constant, avoiding the need for top temperature monitoring and compensation.

Bandwidth versus distance resolution

The bandwidth of the RADAR needs to be high in order to achieve a good distance resolution, and in particular to separate different targets (target-layers) at slightly different distances. Using our ultra-wideband data, the effect of bandwidth can be studied by choosing a subset with smaller bandwidth in the data processing.

This study has been carried out in Figure 8, where the distance spectra are shown for 3 different bandwidths, i.e. 5, 20 and 49GHz. The first pair of peaks (around x = 2560 mm) correspond to the front and back surfaces of the RADAR lens, and the second set of peaks (around x = 2900 mm) to the front and back surfaces of the mould powder layer. As evidenced by Figure 8, the small bandwidth of 5 GHz is unable to resolve the front and back surfaces, resulting in just a single, wide reflection peak for lens and similarly for mould powder layer.

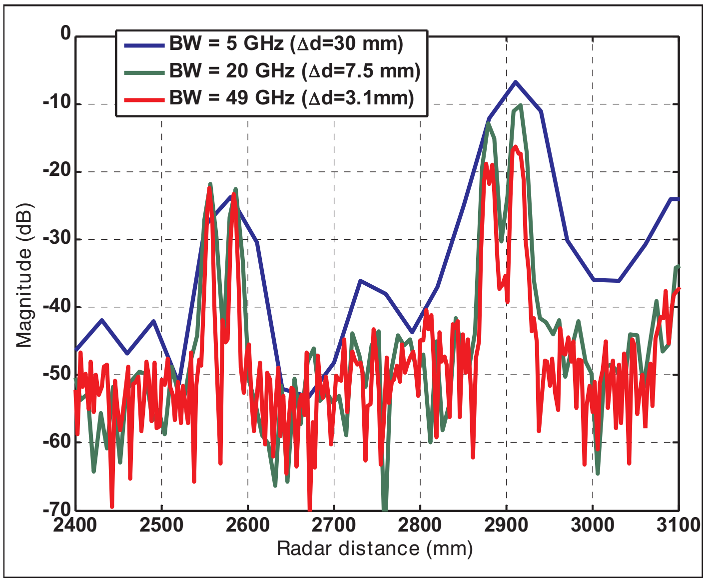

Fig. 8: Effect of bandwidth on the ability to distinguish targets at different distances

The differences between the spectra from bandwidth 20 and 49GHz are more subtle; here the level in between the peaks is lower for the highest bandwidth. The enhanced separation for the highest bandwidth becomes more important for proper distinction of the front and back surfaces when the mould power layer becomes thinner.

In the practice of continuous casting, a lower limit for the mould powder/slag layer thickness is 30mm and since this thickness corresponds to an electrical thickness of around 100 mm (see Figure 7), a bandwidth of 20 GHz with target-to-target separation of 7.5 mm will suffice to resolve the front and back surfaces and hence to deduce the thickness from the radar measurement.

Conclusions & Outlook

It has been demonstrated that an ultra-wideband radar system with bandwidth exceeding 20 GHz, in combination with extensive pre-processing of the data, is capable to detect and distinguish reflections from steel and mould powder. RADAR-based level measurements on liquid steel were shown to attain 1 mm resolution over a working range of more than 150 mm.

The temperature resolved refractive index data of mould powder/slag, which have been deduced from laboratory measurements with the RADAR system and presented in Figure 6 in this article, are shown to be essential to convert the electrical layer thickness, as measured by RADAR, to the conventional geometrical layer thickness.

Future work will look into the possibility of extending the RADAR spot measurement to arrays of RADARs to achieve imaging of the meniscus and slag layer thickness. In addition, trials will be performed to simulate closer the actual conditions in continuous casting to validate the applicability of the technology for industrial use.

References

1. F.D. van den Berg, Haibing Yang: Real-time Meniscus Level and Slag Thickness Measurement by RADAR - Part I: System Design and Characterisation, NDESAI-2011, these proceedings
2. H. Litterscheidt in 'Gießen und Erstarren von Stahl III', Untersuchung des Verhaltens von Gießpulver beim Stranggießen, Abschlußbericht, EUR 8569, Forschungsvertrag Nr. 7210.CA/112, Verein Deutscher Eisenhüttenleute, Düsseldorf, 1984.