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Review

Microwave Technology in Steel and Metal Industry, an Overview

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In many metallurgical operations, effective analysis of the processes can be very difficult with available technology. This is especially true if the analysis is to be performed on-line and in a harsh environment characterized by high temperatures, dust and liquid metal. Protection of the equipment requires both rugged encapsulation as well as elaborate sampling systems and exposure of the equipment to the hazardous environment must be minimised. Often this result in an increased level of service and maintenance requirements and, in the worst case, the maintenance cost might be so high that the equipment is not installed. Microwave technology is a versatile and powerful tool with many different applications in the scientific community. It is insensitive to dust and fume and, for several years, the technology has been tested at MEFOS and evaluated for different metallurgical processes. It has been applied to slag thickness measurement and slag composition in an induction furnace, 3D imaging of the burden surface in a charging model on pilot scale as well as raceway depth measurements in a Blast Furnace. The idea of using microwave technology for gas analysis in metallurgical processes has also been explored. However, despite its many advantages, microwave technology is still not employed extensively in the steel and metal industries.

KEY WORDS: microwave technology; antenna; patch antenna; interferometry; slag; refractive index; conductivity.

1. Introduction

One of the unique properties of electromagnetic radiation is its ability to propagate through matter. In addition, electromagnetic waves will change phase and amplitude as well as polarization in a way representative of the nature of the matter that it passes through. Therefore, gaseous, solid or liquid matter will emit or absorb electromagnetic radiation according to composition, temperature, and molecular structure as well as the electromagnetic field to which it is exposed. Because these changes in the polarization and pattern of wave modulation are characteristic of the matter of interest, electromagnetic radiation can be considered to be one of the most sensitive probes in physics.

If a microwave signal is transmitted towards and reflected by, for example, a steel surface the phase of the signal will change linearly with frequency since a delay between the reference and object signals offset from zero in the time plane will correspond to a slope of the phase in the frequency plane. If the signal is transmitted towards semitransparent matter, part of the signal will be reflected and part of it will be refracted and subsequently propagated through the matter, to be reflected at the next surface where the index of refraction is again changing. These multiple reflected waves will, when cross-correlated with the reference signal, show a complicated curve of phase as a function of frequency. If data therefore are sampled as complex cross-correlated amplitudes in frequency channels over a frequency band, then the distances to both or all the surfaces can be recovered. If the signal is transmitted and received by an interferometer in the aperture plane, a full three dimensional structure of the volume can be reconstructed. If data are sampled from a single point only, then only the thickness information can be reconstructed. Microwave technology is a versatile and powerful tool in the scientific community. For decades, it has been used by astronomers in their work to size and analyse the universe in order to help map and understand its' complexities. In **Fig. 1** is an image showing the red shift in a molecular cloud in the Orion Nebula derived using microwave technology.

On the laboratory scale, it is used by spectroscopists to examine the properties of atomic and molecular compounds and, of course, it has been instrumental in the world of telecommunication as well as mobile phones.

Microwave technology is generally insensitive to dust and fume and therefore it is well fitted for measurements in

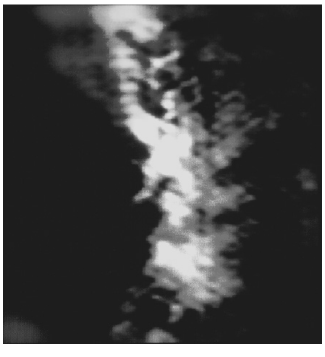

Fig. 1. Molecular cloud Orion Nebula: (with the courtesy of Prof. Lars Bååth, University of Halmstad).

metallurgical processes. In this paper trials performed by MEFOS will be discussed as well as the so far employment of microwave technology within the steel and metal industry.

2. Measurement Principle (General)

When an electromagnetic wave crosses an interface between matters with different refractive indexes, some part of the wave is reflected and some part refracted. The transmitted signal can be described mathematically as:

$$U_{\text{transmitted}}(\omega)=A_0e^{j\omega t} \quad (1)$$

and, the received signal can be written as:

$$U_{\text{recieved}}(\omega)=A_1e^{j(\omega t+\varphi_1)}+A_2e^{j(\omega t+\varphi_2)} \quad (2)$$

where ϕ_n are phase delays related to the interface between the media and A_n represents the reflected complex amplitudes (voltages) of the signal reflected from the surfaces.

By proper signal treatment the distance to a top surfaces as well as the distance to an underlying surface can be established and therefore, the thickness of the matter in between. In the latter case the dielectric properties of the matter must be known.

3. Microwave Technology; Research and Applications

3.1. Slag Performance

In pyrometallurgical processes, slag plays an important role and is responsible for a number of different process steps which are both physical and chemical in nature. In this respect it is important to know both the thickness of the slag and its composition, especially in secondary steelmaking.

Trials have been performed at MEFOS[1)] with the long-term objective of using microwave technology to quantify metallurgical slag performance in a specific processing step during steel production. This work focused on measuring the refractive index and therefore the dielectric properties of the slag. Both industrial and synthetic slags were investigated and with the industrial slags delivered from a number of different steel makers.

The trials were performed in an induction furnace with a nominal capacity of 100 kg and seven frequency bands, each with a bandwidth of 4 GHz, ranging from 2 to 18 GHz were investigated. A Vector Network Analyser was used as a frequency generator during the trials. In this experimental set-up the frequency signal is transmitted and received in the same antenna. The experimental set-up, with a broadband 2–18 GHz microwave antenna, to the left in the photograph, suspended above the furnace, can be seen in **Fig. 2**. In **Table 1** some results for EAF, LD and ladle slag (low alloy steel) are presented.

As can be seen from the table the number of results for EAF and LD slags is low whilst the number of results for ladle slag is relatively high. This gives a success rate varying between 30% and 100%. The magnitude of the refractive indexes derived varies roughly between 1.5 and 4. The individual variations in magnitude of the indexes may, to some extent, be explained by the measurement technique: seven frequency bands were investigated and each frequency band investigated was divided into 501 frequency channels each with a bandwidth of approximately 8 MHz. By averaging the values for the 501 channels for each frequency band, a value of the refractive index for that band was derived. Therefore the derived values of the refractive indexes should be considered as an average value of a frequency band rather then a refractive index related to a single frequency. For some frequency bands no data could be obtained, as can be seen in Table 1, and so far no scientific explanation has been found to explain this. However, here the impact of the slag conductivity, temperature impact as well as the wavelength must be taken into consideration. The results from trials performed on different mixtures of synthetic slag, reported elsewhere,[1)] show a similar pattern to the industrial slags.

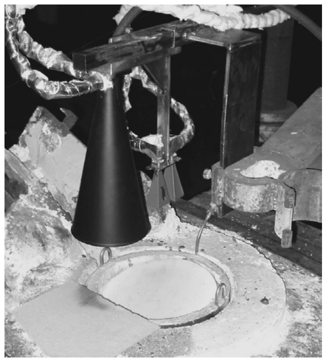

Fig. 2. Experimental set up with two different sets of antennas suspended above the furnace.

Table 1. Refractive indexes, liquid slag.

	Frequency Bands (GHz)						
Slag	2-6	4-8	6-10	8-12	10-14	12-16	14-18
	Refractive indexes						
EAF		1,8	2,5				
Ladle	1,5	1.4	1,9	1,5	1,6	1,6	2.0
LD	3,6	2,4	2,7				

The results so far indicate that the technology used appears to be a viable methodology for slag thickness measurements and slag analysis, although more investigations are required before this can be confirmed.

3.2. Blast Furnace Application

Microwave technology or radar technology are regularly used today in the Blast Furnace for stock rod (level) measurements, burden profile measurements as well as hot metal level measurements in the torpedo ladle.

Other possible applications with microwave technology in the BF are raceway variations and 3D imaging of the burden surface during production. Raceway measurements have been performed by MEFOS at BF 3 at SSAB in Luleå, Sweden. The results of these trials will be presented fully elsewhere[2)] but they will be outlined in this paper.

In **Fig. 3**, the experimental set up shows that that the microwave antenna is integrated into the blowpipe with the electronic unit positioned outside. The electronic unit and

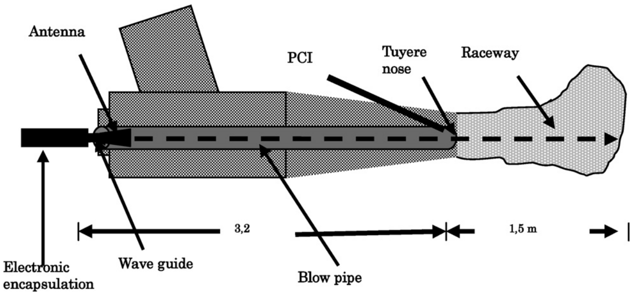

Fig. 3. General view of the experimental set up.

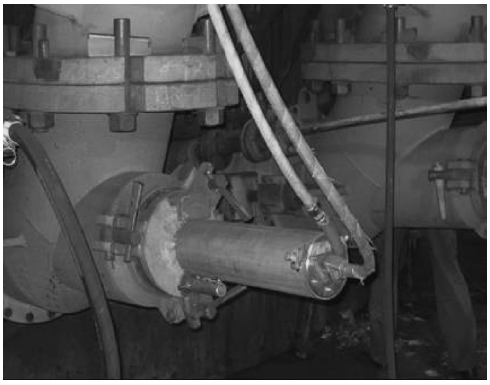

Fig. 4. The microwave unit installed on the BF.

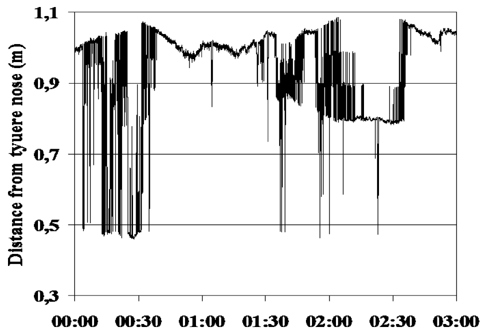

Fig. 5. Raceway depth measurements.

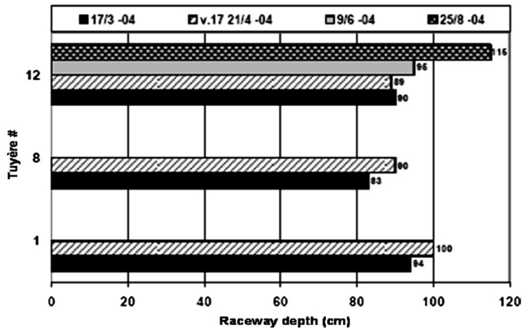

Fig. 6. Core drilling measurements.

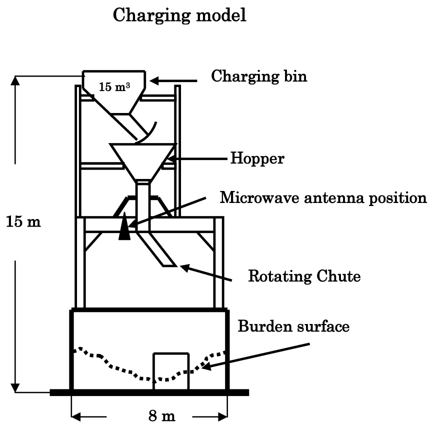

Fig. 7. The charging model.

the antenna are connected to each other *via* a waveguide. The electronic unit is also connected to a computer *via* a signal cable and the unit is purged with nitrogen to avoid overheating.

For these investigations a nominal frequency of 10 GHz was used. The frequency generator was the same as for thickness measurements but the antenna was a corrugated conical horn antenna for this frequency band. The depth of measurement was approximately 1.5 m measured from the tuyere nose to a position beyond the raceway wall. As can be seen from the photograph in **Fig. 4**, this layout is well-suited to be permanently integrated into the blowpipe.

From the graph in **Fig. 5** it can be seen that the measured level varies between 1 and 1.1 m during 3 h operation. The dips in the graph resulted from the instrument occasionally locking-onto a level that was close to the tuyere nose. The reason for this is still not fully evaluated but the PCI is excluded for this phenomenon.

The raceway variations, measured with microwaves, compared favourably with core drilling measurements showing a well-correlated conformity and a depth of approximately 1 m, see **Fig. 6** for core drilling levels for tuyere #12.

Trials to measure the raceway variations have also been reported in another project[3] in which the experimental approach is slightly different although the same frequency range is used. Results from both projects show clearly that microwave technology has the potential to measure raceway variations during Blast Furnace operation.

Another use of microwave technology in the Blast Furnace is to use a planar patch array antenna as an interferometer to create a 3D image of the burden surface. One idea with this approach is to use the image to control the charging sequences and thus optimize gas utilization in the furnace. Trials on pilot scale have been performed and reported by MEFOS in a recently terminated ECSC project.[4] These trials were performed in a full scale charging model at Dillingen Hüttenwerk in Germany. In **Fig. 7** a schematic of the charging model is shown. In the figure the position of the microwave unit is indicated.

As a part of the project, a specially-designed planar patch array antenna was developed for radar interferometry. It is built up by a ceramic-loaded Teflon substrate with a diameter of 180 mm and with 32 rectangular patch antennas integrated onto it, see **Fig. 8**.

Each patch antenna is individually coupled to the electronics. By using one patch as a transmitting antenna and receiving with the others and by repeating this consecutively for all the antennas it is possible to generate interferometric images of the burden surface. **Figure 9** shows a schematic of the antenna positioned above the burden surface.

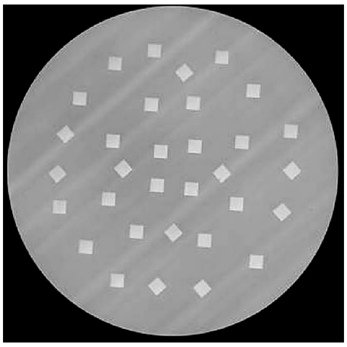

Fig. 8. Interferometer patch array antenna.

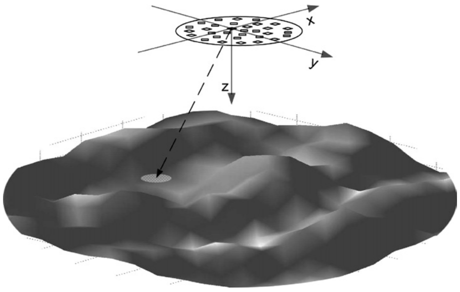

Fig. 9. The antenna positioned above the burden surface.

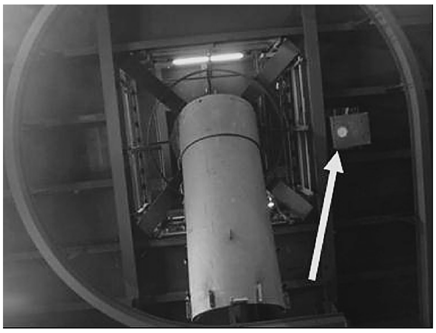

Fig. 10. Patch array antenna mounted in the charging model.

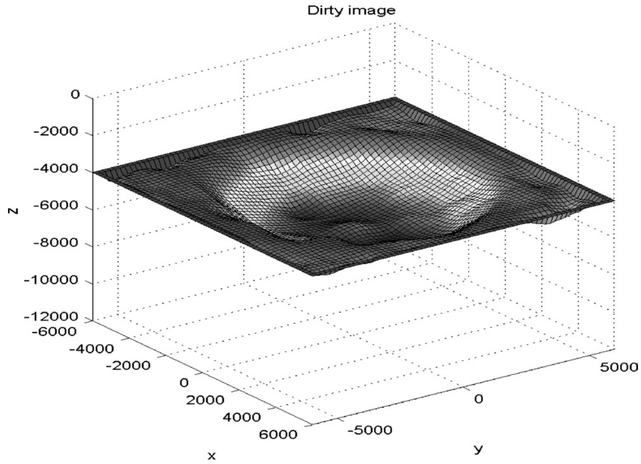

Fig. 11. Dirty image of data from pilot trials.

The interferometer approach was chosen since the harsh environment inside the furnace during production prevents the use of conventional camera technology. A more comprehensive description of the interferometer operation is to be presented elsewhere[5] and is therefore omitted here.

Figure 10 shows a photograph of the antenna installed in the charging model close to the rotating chute. The white point is highlighted indicated with an arrow,

Figure 11 shows a dirty image of the surface in the pilot model. The quadratic shape is related to adjustment to the coordinate system and does not represent the geometry of the pilot facility.

The results from these trials are promising and development of both software as well as hardware for the antenna is continuing.

3.3. BOF Performance

In the BOF, microwave technology has been used to detect the level of the slag emulsion as well as the nominal steel level during blowing.[6] The results of these trials were very promising and showed that different levels in the converter could be detected simultaneously during oxygen blow. Despite this, no follow up of the trials was performed. Recently, in a conference paper[7] the possibility to use microwave technology to control a LD-KG-converter has been investigated. It was reported that the microwave technology used could distinguish between different levels of emulsion and slag in the converter during blowing. The effective steel level was also detectable although this was more complex compared to slag and emulsion. The reason for this is described in the paper as the 'turbulence' in the converter. A practical issue that limited the success of the early trials was the onset of hood skulling. Skull build-up in front of the instrument totally blinds it and makes it incapable of carrying-out measurements. Therefore, in order to continue the measurements, the skull must be removed. Although, this practical limitation has an impact on the measurement performance, it is not related to instrument functionality. Therefore, before the technology can be fully utilized on a converter this problem must be addressed and solved.

3.4. CONARC

The CONARC steelmaking process has been developed by Mannesman Demag. It combines electrode arc melting with the oxygen blowing process. The process consists of two shells with one 3 phases electrode arm and one top blowing lance for the hot metal treatment.

At Mittal Steel Saldanha in South Africa an Agellis BO 1205 Converter Level Measurement System has been installed on the CONARC steelmaking process. The system was commissioned in 2005. The unit is designed to detect the slag and foaming levels in the process during operation. With such an instrument in operation Saldanha believed that slopping would be less frequent, yield would improve significantly and refractory wear would be better controlled. **Figure 12** shows an exploded view of the system.

In this view one can see the antenna and the electronic unit as well as a ceramic disk in front of the antenna. The ceramic disk serves both as a polarizer as well as a shield to protect the electronic from heat radiation from the furnace during production. The part of the encapsulation containing the electronics is purged with nitrogen and the lower part of the encapsulation which is in contact with the furnace roof, is water cooled. The system is used mainly for detecting the bath level before the blow but, because CONARC can be

Fig. 12. Measuring unit BO 1205.

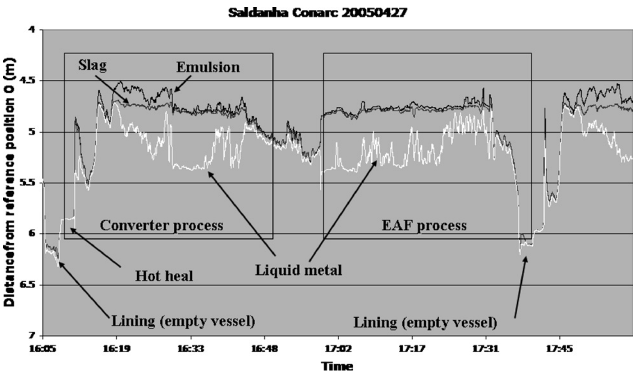

Fig. 13. Process progress (with the courtesy of Saldhana Steel SA).

operated in both EAF and Converter modes, the foaming slag levels are available to the operators during both modes of operation. **Figure 13** follows the progress of CONARC operation.

As can be seen, the slag, emulsion and effective steel heights are all measured simultaneously and in real time.

3.5. Further Applications

Other applications for microwave technology, such as following the height of the steel surface in the tundish, or ladle during tapping are also being examined. For those applications however, no information about the success, so far, has been reported.

Gas analysis is another application investigated by MEFOS. One obvious reason for using microwave technology is that microwaves are normally not susceptible to the presence of dust and fume. Therefore, with a fully functional instrument applied *e.g.* at a converter, it will be possible to perform remote, non-contact cross-duct analysis of the off-gases very close to the converter process and in real time. Conventional extractive technologies normally require elaborate sampling systems which are subjected to continuous service and maintenance and, they introduce an extensive time delay into the gas analysis, which can sometimes amount to minutes. This often makes them inexpedient for process control in real time.

The instrumentation used in this application was a Vector Network Analyser and two frequency converters together with antennas, one up-converter and one down-converter, and some signal amplifiers. Since the frequency generator had a maximum output of 40 GHz this approach was necessary to reach the higher frequency levels of interest. The microwave measurements were performed in a frequency window ranging from 110 to 120 GHz. The reason for this is that CO, CO_2 and O_2 exist within the same frequency range and these compounds are of most interest for converter control. The results from this investigation are still being analysed due to a non-statistically significant mismatch between known frequencies, especially for CO, and the spectral information monitored during the trials. It is important to find the cause for this mismatch before new trials can be performed. In this work one has to take into consideration that the trials have been performed at atmospheric pressure and at high temperatures with all its implications. In this respect, very little has been published that could assist such an investigation. One published article[8] describes CO measuring trials performed at atmospheric pressure. However, in these trials, a Fabry-Perot resonator was used which was not the case in the MEFOS trials.

4. Summary

Microwave applications in the steel and metal industry, to the knowledge of the authors, are in regularly use on the BF and the CONARC processes. No known installations on EAF, BOF and ladles have so far been made public.

Microwave technology is powerful and versatile with applications in many scientific disciplines. The employment of microwave technology in the steel and metals industries however is not extensive. One reason could be that each installation requires a rather unique solution to be applied to be fully functional. This has in general nothing to do with the technology or the functionality of the microwave instrument itself and is more related to impact of the process on the instrument such as hood skulling in the LD process. The technology is also used as an analytical tool to gain new knowledge about processes as in the case of slag and gas analysis. This is work with a direct scientific objective and it will probably take many years before these investigations are completed.

At the present time, microwave technology is within many research disciplines including industry-related applications. As the technology develops with cheaper components, new frequency ranges will be investigated. In this respect, development of new probes and instruments with applications within the steel and metals industries could speed-up employment of the technology and, by investigating new frequency ranges, new parameters could be measured that could lead to new technical applications.

Therefore, despite the present low impact of microwave technology in the steel and metals industries, the future looks bright.

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