Development of Eddy Current Probe using FEM for Matte Level Detection in Pyrometallurgical Furnaces

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Abstract. Pyrometallurgical furnaces are utilized to produce metals such as copper, nickel and platinum by the smelting process. During smelting, the undesired waste materials (oxide) are separated from the desired and economical metal components. The slag phase (impurities and waste) floats on top of the matte phase (molten metal), since the density of slag is lower than the molten metal. The molten metal is then extracted or tapped out of the furnace through tapping channels or tapblocks. It is desirable to monitor the level of molten metal during smelting operations to optimize tapping schedules and thereby, maximize productivity. The molten metal level is most often measured with a manual method, where a sounding bar is inserted into the molten metal bath through a port in the furnace roof. After the extraction of the bar, based on the reaction of the slag and molten metal with the bar, the thickness of each layer is manually determined by measuring tapes. This method depends on human interpretation and is thought to be inconsistent. In addition, the operators must have access to the furnace roof, which increases safety concerns and requires the furnace power to be switched off. This paper describes the modelling of a new eddy current sensor to be installed in the furnace sidewall for the remote detection of molten metal level in the furnace using COMSOL 5.3.

The finite element method (FEM) model was designed using the AC/DC module in COMSOL 5.3 Multiphysics by defining nine cylinders as numeric coils through the Magnetic Fields physics option. These coils were modelled as homogenized multi-turn conductors. A constant amplitude sinusoidal voltage (2.5 V) was applied to the drive coil. A rectangular sheet was placed at a distance of 300 mm from the coils and a partition domain was created to split the sheet into two domains. One domain was assigned as titanium metal and other as air. This was done to model the changing metal level using Parametric Sweep. Using the Frequency Domain and Parametric Sweep study options the voltage in each coil was calculated for different metal heights. The FEM model was also validated with experimental results and good agreement with experimental data was observed. The sensing system, designed with COMSOL, was capable of detecting the molten metal/slag interface at a distance of more than 300 mm, thereby demonstrating the potential for an automated level measurement system embedded in the furnace sidewall that provides improved safety and accuracy compared with manual sounding methods.

Keywords: Pyrometallurgical furnace, Eddy current, Matte or molten metal, FEM, COMSOL Multiphysics.

1. Introduction

The first step in the production of metals in a pyrometallurgical furnace involves the smelting of concentrated ores. This results in the formation of a matte phase (molten metal) and a slag phase (oxides and other impurities). The density of the slag phase is lower than that of the molten metal phase [1]. Accordingly, the slag phase tends to float on top of molten metal phase. It is important to determine the molten metal/slag interface in order to optimize the tapping schedules and thereby, maximize productivity. Tapping decisions are based on molten metal level measurements and thus, reliable and accurate knowledge of molten metal level results in enhanced control of the overall process.

Sounding bars have traditionally been used to measure the molten metal level but suffer inaccuracies since the technique is subject to human interpretation [1-2]. The technique involves immersing a rod is into the furnace bath from the roof and using the visible difference in the color on the rod after removal from the bath to estimate the metal height. Differences in color on the rod are interpreted to be due to different rates of heat transfer between the rod and the metal and slag. Clearly, conductive heating will also take place along the rod, which will be a function of the time the rod is held in the molten metal. The accuracy and repeatability of this method is poor, and it also raises safety concerns for the operator. In addition, this method often requires a furnace shutdown before testing, interrupting furnace production. In recent history, alternative technologies have been developed for the measurement of molten metal level in furnaces [1-9]. However, none of those technologies have been widely commercialized due to many limitations. For example, radiowave sensors for molten metal level detection are unsuitable for furnaces because of high attenuation of the radiowave signal by the slag [9]. Electrochemical sensors – based on the difference between the oxygen potential of the molten metal and the slag – suffer from the restrictive requirements that the probe must be inserted from the furnace roof and the furnace must be shutdown (similar to the sounding rod) [1]. As accurate and reliable data about the molten metal level measurement is important in terms of productivity of the furnace, a safe and continuous method for obtaining this data is an industry priority.

Eddy current testing is a commonly used method for inspecting metallic components [10-11]. Conventional eddy current testing is used for surface or sub-surface characterization of metals [12]. In conventional eddy current testing, the distance between the test piece and the sensor, known as liftoff, is limited to several millimetres [12]. However, there are studies where remote eddy current testing was reported for higher liftoffs, such as sea ice thickness measurements [13-14]. Eddy current technology has the potential to be used for measurement of molten metal level in furnaces, where remote detection is important.

In the present paper, an eddy current sensor has been designed using the finite element method (FEM). The FEM model has been validated with experiments performed using a prototype in the laboratory. FEM simulations can provide significant information about the electromagnetic phenomena and facilitate better understanding of experimental results [15-17]. FEM simulations can also be used to analyse the effect of different parameters that would be challenging and time consuming to conduct as experiments in the laboratory.

2. Use of COMSOL Multiphysics® Software

FEM models were created using COMSOL Multiphysics 5.3 a. All of the calculations were done using the *Magnetic Fields Physics* option of the AC/DC module of COMSOL Multiphysics in the frequency domain. Simulations were performed at 10 kHz frequency and a drive voltage of 2.5 V.

2.1 Overview of the sensor design

The eddy current sensor described in this paper consisted of eight pickup coils and one drive coil at the centre, as shown in Figure 1. Each coil was designed as a cylinder with layers on the side of the cylinder. The diameter of each cylinder was around 60 mm and length 25 mm with a layer thickness of around 2 mm. Each cylinder used a mesh determined by *Physics-controlled mesh* option, while choosing a *Free Triangular mesh* on one face of the cylinder. The size of the mesh was chosen as *Extremely fine*. This *Free Triangular mesh* used for one face of the cylinder was then extended to the full cylinder domain by *Swept Option*. The boundaries of the cylinder were then *Converted* to make them compatible with a tetrahedral mesh. A spacing of 100 mm was maintained between the coils.

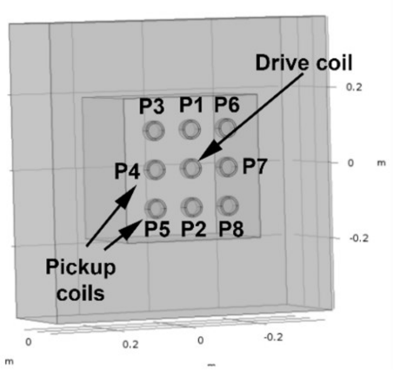

Figure 1: FEM model of the eddy current sensor with eight pickup coils and a centered drive coil.

The coils were designed as a homogenised multi-turn conductor with 98 turns for drive coil and 1000 turns for pickup coils. The *Magnetic Fields* physics option was used to solve for voltage induced in the pickup coils. This was done using *Frequency domain solver* at 10 kHz frequency. The coil wire gauge was selected to be 36 for pickup coils and 24 for drive coil.

2.2 Simulation of molten metal

The sensor described in the previous section was designed to be installed inside the tapblock of a furnace. This sensor was intended to detect the molten metal level from the furnace sidewall. A rectangular sheet was created in front of the sensor at a distance of 300 mm from the sensor setup, as shown in Figure 2. It was partitioned into two domains using *Partition domain* option and the position of the work plane for partition domain was defined by a variable parameter. This parameter was defined in *Global definitions parameter* option. One partition domain was assigned as titanium material and the other one as air. Titanium was chosen because it was expected to have a resistivity greater than that of typical molten metals.

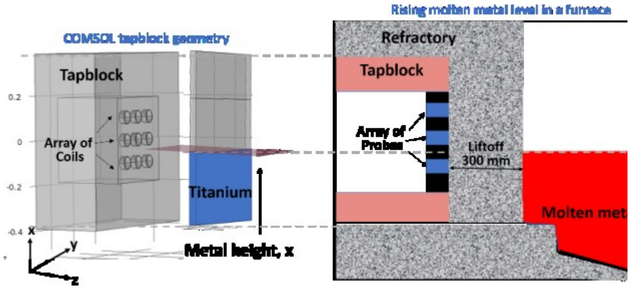

Figure 2: a) FEM model of the sensor located inside the tapblock of a furnace and Ti sheet simulating the molten metal level, b) schematic of a furnace indicating the molten metal level and the tapblock position.

A *Parametric sweep* was used to vary the position of the partition domain work plane, thereby changing the dimensions of the partition domains. This was done to run the simulations at different heights of titanium, simulating the molten metal level in a furnace. The signal generated by the drive coil created eddy currents in the titanium metal and these eddy currents affected the signal received by the pickup coil [10]. The voltage received by the pickup coils was extracted from the software and plotted against metal height, as shown in Figure 3.

The signal amplitude increases as the metal height is increased for pickup coil P2 until it reaches saturation, as shown in Figure 3. In contrast, the signal for pickup coil P1 is negligible up to 200 mm metal height and increases after that. This is because P2 is the bottom coil and it senses the metal at earlier stages and then saturates when the metal height is above the P2 coil position. On the other hand, P1 is at the top position and senses the metal later when the metal height is more than 200 mm. Similarly, other pickup coils show different trends based on the position of the coil with respect to the drive coil and metal height. Hence, based on the signal response of these pickup coils, the metal height can be estimated in an actual furnace.

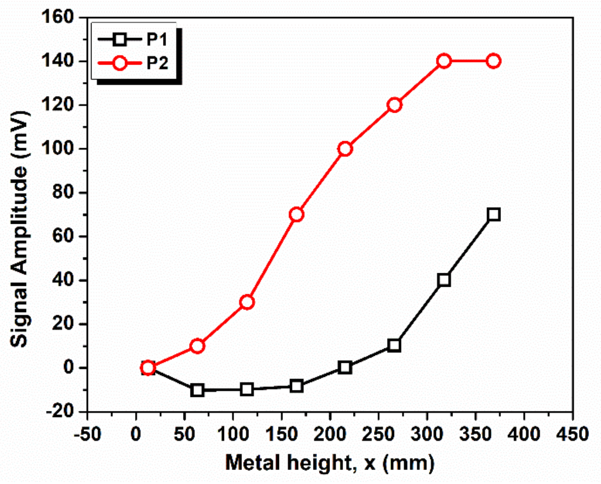

Figure 3: Signal Amplitude received by the pickup coil as a function of titanium sheet height simulating the molten metal inside a furnace.

The path of magnetic flux lines and their interaction with the rising metal is shown in Figure 4. At zero metal height, the field is not affected by the metal and therefore, no relative change is received by the pickup coil. As the metal height increases, the field lines are intersected by the metal. The corresponding change in the field is sensed by the pickup coil.

3. Experimental Setup

To validate the FEM model, experimental measurements are required. This was achieved by preparing drive and pickup coils in the laboratory and testing the effect of a Ti sheet on the signal. The dimensions and coil number of turns were similar to that used in the COMSOL FEM model. The coils were placed inside an Al box simulating the tapblock in an actual furnace. The dimensions of the titanium sheet were 940 mm long, 180 mm wide and 5 mm thick.

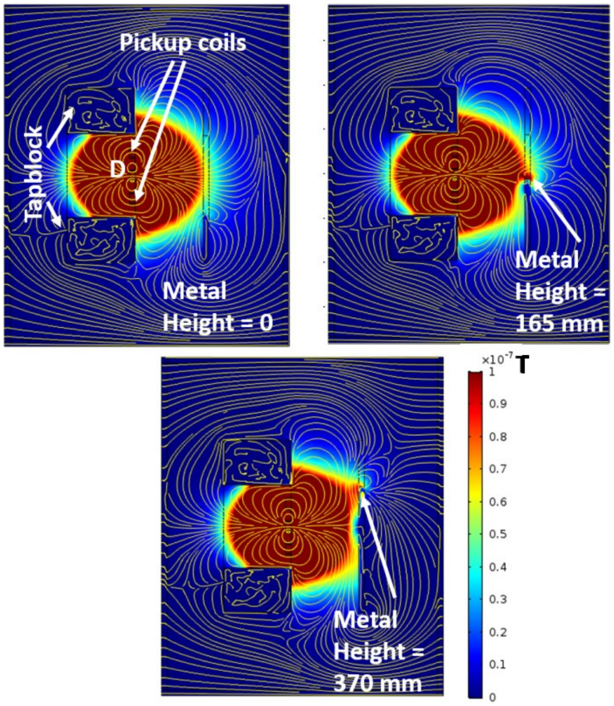

Figure 4: Magnetic flux density and magnetic flux lines through the drive coil and the effect of Ti sheet on the signal. This is the xz plane passing through the centre of the drive coil in Figure 2.

The drive coil was placed at the centre and pickup coil was placed at positions from P1 to P8, as shown in Figure 5. The titanium sheet was moved from zero metal height position to 380 mm metal height. The long edge of the titanium sheet was parallel to the axis of movement and a liftoff of 300 mm was maintained during the experiment.

4. Experimental Validation

The results from the experiment were compared to the COMSOL simulation results, as shown in Figure 6. The trend of the curve obtained with experiments was similar that of the COMSOL results, when the magnitude of the simulation results was scaled by a constant scaling factor. This was done to compensate for unknown gains in the eddy current instrument. In addition, COMSOL's treatment of coil density is undefined and coil turns are perfectly homogenised, whereas this may not be the case with manual coil preparation. Good agreement between the experiments and scaled simulations was obtained.

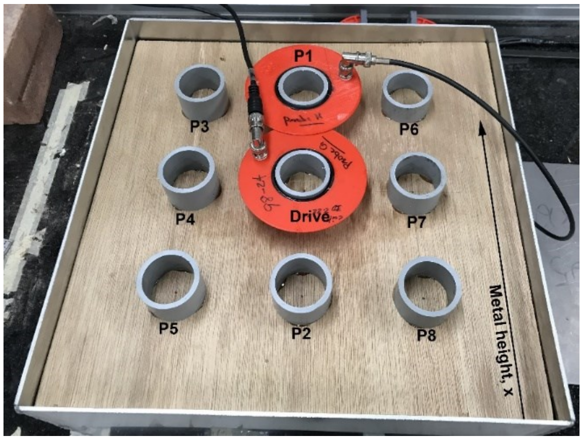

Figure 5: The position of drive and pickup coils inside the Al tapblock.

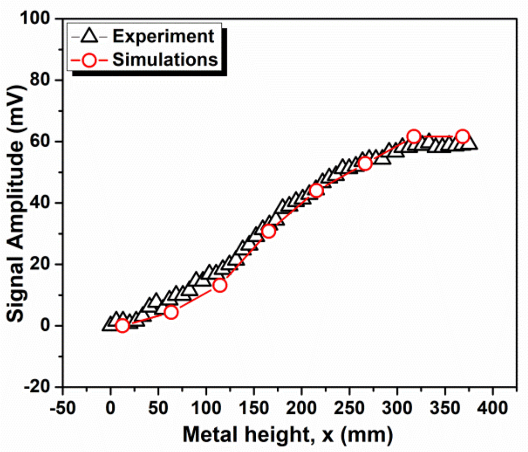

Figure 6: The signal amplitude as a function of metal height for P2 derived from experiments and COMSOL model.

5. Summary

The eddy current technology described in the present paper has the potential to be used for the measurement of molten metal levels in pyrometallurgical furnaces. The eddy current sensor was successfully modelled in COMSOL and validated using a prototype in the laboratory. It demonstrated the capability of measuring molten metal level at 300 mm liftoff. The use of COMSOL in the sensor design permits modification of the sensor according to the furnace requirements, without the need to physically perform the challenging experiments in a laboratory setting.

References

1) J. M. A. Geldenhuis, D. Miller, B. Van Beek, J. Ndlovu and K. T. Hara,”Development of alternative techniques for matte level measurements in sulphide smelting furnaces”, *International Platinum Conference ‘Platinum Adding Value’*, The South African Institute of Mining and Metallurgy, pp. 25-32, 2004.

2) T. J. Goff, N. Brogden, J. P. Nilsson, P. Bloemer and A. Lyons, “Implementation of an alternative matte-level measurement solution at Lonmin Marikana Smelter Division for improved process monitoring”, *South African Pyrometallurgy*, Edited by R. T. Jones & P. den Hoed, Southern African Institute of Mining and Metallurgy, Johannesburg, pp. 269-284, March 6-9, 2011.

3) N. Brogden, P. Jakobsson, P. Bloemer, A. Lyons, C. Doyle, R. Aquino, R. J. Dijkhuis and E. Floch, “Electromagnetic level profile measurement system at Vale ONCA PUMA ferronickel smelter improves safety and enhances process control decision making”, *The thirteenth International Ferroalloys Congress*, Efficient technologies in ferroalloy industry, Almaty, Kazakhstan, pp. 215-222, June 9-13, 2013.

4) A. P. Evteev, “The sensors for System of Automatic Maintaining Molten Metal Level in Casters”, *Proceedings of the* 6^{th} *Congress of Steelmakers,* pp. 600-604, published in Russian, 2001.

5) N. I. Shestakov, Y. P. Kostin and N. A. Dobrosmyslov, “Ultrasonic Sensors for Level Control in Continous Casting”, *Proceedings of the Universities, Ferrous Metallurgy*, vol. 9, pp. 1-15, 1982.

6) J. Madias, R. Villora, H. Stafforte, O. Sparapani and M. Dziuba, “High Speed Continous Casting of Low Carbon Steel Billets”, *1996 ISS Steelmaking Conference Proceedings*, vol. 79, pp. 315-319, 1996.

7) B. G. Thomas, M. A. Wells and D. Li, “Monitoring of Mensicus Thermal Phenomena with Thermocouples in Continous Casting of Steel”, *Sensors, Sampling and Simulation for Process Control*, editors B. G. Thomas, M. A. Wells and D. Li, John Wiley and Sons, Inc., Hoboken, NJ, pp. 119-126, 2011.

8) F. S. V. Gomes, K. F. Côco, and J. L. F. Salles, “Multistep Forecasting Models of the Liquid Level in a Blast Furnace Hearth”, *IEEE Transactions On Automation Science And Engineering*, pp. 1286-1296, April 2017. DOI: 10.1109/TASE.2016.2538560.

9) W. Braun, D. Chataway, J. Janzen and A. Kepes, “Feed and Charge Level measurements in Furnaces”, *Proceedings of EMC*, pp. 1-11, 2017.

10) N. M. Rodrigues, L. S. Rosado and P. M. Ramos, “A portable embedded contactless system for the measurement of metallic material conductivity and lift-off”, *Measurement 111*, pp.441-450, May 2017.

11) J. Yin, M. Lu, and J. Piñeda de Gyvez, “Full-Signature Real-Time Corrosion Detection of Underground Casing Pipes”, *IEEE Transactions On Instrumentation And Measurement,* vol. 49, no. 1, pp. 120-128, February 2000.

12) T.W. Krause, R.J McGregor, A. Tetervak and R. Underhill, “Pulsed eddy current sensor for precision measurement at-large lift-offs on metallic surfaces”, *Patent No. US 9,091,664 B2 Filed on Jun. 7, 2012*, Appl. No. 13/490,795, Jul 28, 2015.

13) C. Haas, J. Lobach, S. Hendricks, L. Rabenstein and A. Pfaffling, "Helicopter-borne measurements of sea ice thickness, using a small and lightweight, digital EM system," *Journal of Applied Geophysics*, vol. 67, no. 3, pp. 234-241, 2009.

14) A. Kovacs, N. C. Valleau and J. S. Holladay, "Airborne electromagnetic sounding of sea ice thickness and sub-ice bathemetry," Cold Regions Science and Technology, vol. 14, no. 3, pp. 289-311, 1987.

15) P.R. Underhill and T. W. Krause, ‘Finite Element Model Study of the Effect of Corner Rounding on Detectability of Corner Cracks using Bolt Hole Eddy Current’, 43rd Annual Review of Progress in Quantitative Nondestructive Evaluation, Vol. 36,(Ó 2017 AIP Publishing), AIP Conf. Proc. 1806, Pgs. 110006-1-110006-8.

16) V. K. Babbar, P. R. Underhill, C. Stott and T. W. Krause,‘Finite Element Modeling of Second Layer Crack Detection in Aircraft Bolt Holes with Ferrous Fasteners Present’,Nondestructive Testing and Evaluation International, 65, July 2014, Pgs. 64-71.

17) V. K. Babbar, B. Lepine, J. Buck, P. R. Underhill, J. Morelli and T. W. Krause, ‘Finite Element Modeling of Wall-Loss Sizing in a Steam Generator Tube Using a Pulsed Eddy Current Probe’, AIP Conf. Proc. 1650, 1453-1459 (2015).