A wireless sensor system based on surface acoustic wave (SAW) technology has been developed to measure the temperature inside a refractory lining of a metallurgical vessel. The components of the sensor unit are designed for harsh environments to withstand moisture and high temperatures. The sensor signal, which contains an identification number and the temperature, is transmitted through the steel shell of the vessel via a robust cable link from the SAW sensor to the transponder antenna. A continuous wave reader unit interrogates the sensor unit and processes the signal for the recording unit. The sensor unit has been tested in a drying sequence of a castable refractory lining. The design of the sensor unit and the results are presented in this paper.

Keywords: metal, vessel, sensor, wireless, SAW, high temperature
be requested via a radio signal, are robust and can endure elevated temperatures up to 400°C [2]. As a further advantage, SAW sensors are passive devices and earn their energy from the electromagnetic request signal, hence no battery is needed. Together with reasonable read out ranges SAW sensor systems are well suited for industrial applications like torque sensing [3], tire pressure monitoring [4] or temperature monitoring of power transmission lines [5]. Beyond that SAW transponder systems operating in the ISM-band at 2.44 GHz have also the ability to transmit an identification number and can thus be used for classical radio frequency identification (RFID) tasks under severe environmental conditions e.g. steel plant [6].

2. Sensor unit

As it is not possible to transmit radio frequency (RF) signals through the metallic shell (e.g. 20 mm steel) a modular sensor design was developed, as shown in Fig. 1. The sensor head, which contains the SAW sensor, is connected via a robust coaxial cable to the transponder antenna. Two magnets on the transponder antenna are used to attach the sensor unit to the steel shell. Different cable lengths can be used as different locations of the sensor head in the lining are of interest. Fig. 2 shows two sensors with different cable lengths.

The SAW sensor consists of a reflective delay line on a LiNbO₃ substrate crystal with an aluminum based metallisation, packaged in a metallic housing with two glass feedthroughs. To protect the device from the aggressive atmosphere emerging during the drying process it is encapsulated in the sensor head, which is a moisture-tight steel cap. For the signal transmission a semi-rigid coaxial cable with a steel mantle, center conductor and a polytetrafluorethylene (PTFE) dielectric was selected. The link to the sensor and to the transponder antenna is realized with water resistant RF connectors. All gaskets are made of Viton® seals. To achieve maximum temperature stability the whole sensor assembly is free of any soldered junctions. The electrical interconnections are realized by laser welding in combination with crimp contacts.

3. System configuration

The temperature is monitored in the wear lining as indicated in Fig. 3. Via the external reader antenna the initial radio frequency (RF) signal is transmitted from the reader unit to the sensor unit, returning the signal with the sensor information. The reader unit is a four channel continuous wave radar (CW-radar) [7]. It decodes the RF signal into the identification and temperature data, which are recorded by a computer. The antennas on the reader side are located opposite the transponders. The read out range can vary from 10 cm to 100 cm. On the reader side no high temperatures are expected, so a conventional patch antenna could be used. Due to the selected transponder type, which transmits a temperature value as well as an identification code, only one transponder can be located within one antenna beam. Thus care has to be taken that different transponder and reader antennas do not interfere. A detailed list with the targeted specifications of the sensor systems is shown in Table 1.
Table 1. Specification of the sensor system

| Specification                                      | Value                      |
|----------------------------------------------------|----------------------------|
| operation temperature (sensor head)                | -20°C to +250°C            |
| operation temperature (transponder antenna)        | -20°C to +150°C            |
| operation temperature (reader antenna)             | -20 to +60°C               |
| operation temperature (reader unit)                | -20°C to +55°C             |
| max. read out range                                | 1 m                       |
| sensor head dimensions                              | 20 mm (dia)                |
| sensor head dimensions                              | 30 mm (length)             |
| cable length                                       | 10 cm to 100 cm            |
| antenna size, cross section (sensor & reader antenna)| 10 cm x 10 cm             |

4. Measurement results

The sensor unit was tested in a drying sequence of a tundish wear lining. A tundish is a metallurgical distribution vessel for molten steel. During the drying process hot water, steam and exhaust fumes are released by the lining, therefore the sensor unit must be steam tight. The steam tightness was verified in a lab trial, where the sensor unit was exposed to hot steam for 12 hours. The wall of the tundish used consisted of a steel shell with a thickness of 20 mm and a permanent lining with a thickness of 135 mm. The sensor unit was inserted into a hole of the tundish wall and the transponder antenna was attached to the steel shell with the magnets. Afterwards the castable was mixed with water and applied to the inner wall with a thickness of approximately 40 mm. With the selected cable length the sensor head reached into the wear lining by 30 mm and was covered with 10 mm castable.

The tundish was dried for 180 min with a gas burner, until the exhaust fumes had reached a temperature of 600°C. These are the standard parameters for such a tundish configuration. The SAW signal was stable during the whole time and showed temperatures of 250°C and above, as shown in Fig. 4. Although the magnitude of the SAW signal decreases with elevated temperatures, it is still possible to decode the data at a range of 10 cm. An example of an impulse response of the SAW sensor at 246°C is shown in Fig. 5. At the outer wall of the vessel maximum temperatures of 56°C were measured. With 21°C the reader antenna temperature was already near the ambient air temperature.

There are several reasons why the SAW sensor temperature is lower than 600°C. First, the wear lining is an insulating ceramic with a low thermal conductivity, which creates a rather large temperature gradient and the sensor head was not directly mounted at the inner end of the lining. Second, the SAW sensor itself is protected by a 30 mm
long steel cap, having an averaging effect on the temperature of the SAW device. In the next step to adapt the sensor
unit for the practical use the temperature trend has to be calibrated with standard measurement methods [1].

**Conclusions**

A sensor for monitoring the temperature inside a refractory lining through a steel shell has been developed and
tested experimentally. The sensor system is based on SAW sensor technology, whereby the temperature and an
identification number are interrogated wirelessly via a radio signal. Ongoing efforts are undertaken to miniaturize
the packaging and the protective steel cap to increase the thermal dynamics of the sensor.

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