Findings:

<u>Experimental Studies: sensor strip attachment and electroplating embedding</u>

- The wireless system was tested in the presence of an electromagnetic field at a commercial steel company and was shown to maintain communication between the thermocouple node and base station transceiver.
- During the initial plating study, nickel adhered well to the top, bottom, and sides of the nickel strip, as well as the copper substrate, as depicted in Figure 2 of the attached report.
- Often, when electroplating onto a thin strip suspended a small distance from the substrate, a void commonly forms in the gap, due to the starvation of nickel atoms when two sections of growing grains impinge just past the edge of the nickel strip. This also causes the void width to extend wider than the strip width, seen as seams at the edge of the void.
- The rate of plating is greatest in areas where sharp corners exist, due to higher current density.
- More plating reaches under the nickel strip as the sensor width decreases and/or gap thickness increases. More specifically, more plating reaches under the nickel strip as the aspect ratio, defined as the strip width over gap thickness, decreases.
- Complete filling under the nickel strip is predicted to occur when the aspect ratio is less than or equal to one.
- A sensor strip can be attached to a copper substrate via conductive silver paste and successfully plated over without any air gaps. However, the time and skill involved in this process is considerable.
- According to the ultrasonic welding equipment manufacturer, past experiences have indicated that ultrasonic welding near, around, or on top of sensors has lead to irreversible damage.
- Although the ultrasonic welding equipment is able to attach the two dissimilar metals, the machining pattern caused by the weld horn is unavoidable.
- Due to their non-conductivity and geometry, fiber optic sensors can be plated over without an air gap developing (Figure 4 of the attached report).

<u>Modeling Studies: Consequences of Gap Formation and Initial Solidification Phenomena</u>

- It was found that an air gap in the nickel plating layer can cause stress to increase by 19%.
- A wider gap makes it more difficult for heat to conduct around the gap, increasing the temperature at the hotface: doubling the width of the air gap increases the hotface temperature by 65°C, while doubling the thickness of the air gap increases the hotface temperature by only 5°C.
- Oscillation marks and hooks which comprise the initial solidification structure form due to meniscus freezing and overflow. This brings heat to the meniscus in a characteristic periodic heat flux, which is usually increasing during the negative strip time. A detailed computational model of this has revealed the fundamentals of this behavior and a detailed mechanism for the phenomena. This is summarized in 4 publications [1,2-5]

Discovery of New Sensor Technology

- A method to measure temperature and/or heat flux near the surface of the hot face of continuous casting molds has been designed (see Figures 5 and 6 of the attached report). It consists of embedding a thin optical fiber with fiber Bragg gratings inside a thin stainless steel tube into the nickel coating layer during electrodeposition onto the surface of the copper molds used to continuous cast steel slabs and/or billets. During casting, this sensor will monitor the thermal condition of the mold. The sensors inside the fiber function using optical-based technology (resonating frequency of light captured in an embedded optical fiber system causes the wavelength of light emitted along the fiber to depend on thermal strain, which varies with the temperature). Embedded sensors have the advantage of real-time monitoring at critical locations as well as immunity to electromagnetic interference and resistance to hostile environments, but cannot be commercial successful without a robust attachment method. An alternative method embeds a rectangular strip which contains micro- and nano-layers deposited using nano-fabrication technology, that functions using conventional thermocouple technology (difference between the voltages that the temperature induces in two different metals) using conductive silver paste. In either case, the key aspects of the new invention (making it better than existing thermocouples) are
- The small size of the active sensor is much smaller than current thermocouple “beads”, allowing greater sensitivity to temperature variations both spatially and temporally;
- The small size of the entire sensor, allowing accurate knowledge of its position near the surface of the mold;
- The active part of the sensors being embedded into a strip, allowing it to be manufactured in a controlled environment, and handled, prior to attaching to the dirty environment of the mold;
- The attachment method to the mold, consisting of attaching (via embedding into the coating layer) of the sensor to the conditioned mold surface during the electroplating process. This method allows the sensor to be close to (but not at) the mold surface without drilling a hole through the mold. The distance of less than 1 mm from the surface is more than an order of magnitude closer to the hot face surface than conventional thermocouples;
- Extension of the sensor fiber/strip beyond the top of the mold, allowing easy extraction of the sensor signals to a computer, such as by attachment to a miniature circuit box for wireless transmission to a computer located elsewhere.
- The new sensor provides crucial information about the temperature and heat flux state of the mold. It solves several problems inherent to conventional thermocouple systems (currently used to monitor mold wall temperature), and conventional mold level sensors (currently used to monitor mold level). If a second optical fiber is embedded, then the sensor can additionally monitor thermal stresses in the mold surface, enabling it to provide feedback to signal crack formation in the coating layer.