Research and Education Activities:

Work at the University of Illinois has focused on discovering a new technology for implementing better sensors into the continuous casting mold used at the steel plant. This has involved experimental investigation of 1) the attachment of glass fiber and nickel-based sensors onto the copper mold surface, and 2) ability to embed the sensors into the mold coating during the eletro-plating process, and computational modeling investigations of 1) heat-transfer consequences of imperfect plating to determine standards for success, and 2) mechanisms of initial solidification including heat extraction during oscillation mark formation, in order to extract useful results from the finished sensors in the future. The ultimate goal is to discover a new and better sensor technology for in-mold monitoring of the continuous-casting process.

Many of the problems in continuous casting arise during the initial solidification at the meniscus in the mold, including defects in the final cast product as well as cracks in the mold surface due to thermal stress. These problems dictate many aspects of steel quality and productivity. Although the mold hot face is an ideal location to monitor, it presents a very hostile environment, with copper mold surface temperature ranges from 200 to 400^{o}C, with instantaneous spikes that might reach 800^{o}C during a mold level fluctuation. In current industrial practice, a large number of thermocouples are used in one continuous casting mold, destructively inserted into mold through channels drilled in copper mold, far from the hot face due to safety considerations. This limits their usefulness, as their response time is too slow to capture the rapid events that occur at the meniscus due to the dampening of the temperature signal caused by the thick copper mold between the solidifying steel and the thermocouple. Sticker breakout detection systems, installed in almost every caster worldwide, use thermocouple signals interpreted by control systems to take corrective action, but are limited by inadequate sensor technology and insufficient understanding of how to interpret the signals.

The proposed sensors have a temperature accuracy of +/- 2^{o}C and a 0.01s response time, capable of capturing temperature fluctuations of greater than 100^{o}C in 0.1s, much more sensitive than conventional thermocouples, and are designed to measure heat flux and temperature within 1 mm of the meniscus to more accurately predict level fluctuations and quality problems, as well as providing additional insights into the casting process. Improved versions of the sensor strip design and manufacturing process are being developed through collaborations between the University of Illinois, where the sensor design, modeling, testing, evaluation, and implementation is being coordinated, the University of Wisconsin-Madison, where the sensor strip will be fabricated, a commercial mold manufacturer, where the strip will be attached to a commercial mold, and a commercial steel company, where the mold and sensor will be tested in service.

In sum, this project aims to develop and validate a new type of in-mold sensor for use in the commercial continuous casting of steel. The aim is 1) to revolutionize online thermal monitoring of industrial continuous casting molds and 2) to create a new research tool to investigate meniscus behavior so that defect formation can be better understood.

A preliminary design for the sensor and its installation into a continuous casting mold is proposed (see attached report). The sensor pad containing the wire junction points will protrude out of the top of the copper mold and nickel plating, thereby making wire connections possible after plating. These wires will be run a short distance to a wireless transmitter which will transmit the signal to the control-room operator display or other computer. A wireless thermocouple system that is compatible with the sensor was obtained from MicroStrain. The system supports simultaneous data transmission from multiple sensors, theoretically allowing thousands of sensors to be installed into a mold.

Experimental Studies: sensor strip attachment and electroplating embedding

Before any research can be carried out to understand the behavior of embedded sensors, it is imperative that a robust method be developed to embed sensors in manufacturing tooling. Therefore, there is an absolute need to refine the embedding process through plating studies, as the sensor strip will be attached to the copper mold via the electroplating process used to apply the nickel coating layer. Any attachment method must provide a secure bond between the sensor strip and the copper mold face, have no air gaps, survive the acid pretreatment steps, and allow the sensor strip to be plated successfully before the copper mold can be put into service. It is possible to attempt to plate the sensor strip, which is fabricated encapsulated by nickel, by placing it on the copper mold face and submerging the mold face into the plating tank of the mold manufacturer. Two different trials spanning a range of aspect ratios were performed to evaluate the plating ability to attach a nickel strip to a copper substrate via commercial nickel electroplating. It was proposed to repeat the initial plating study with aspect ratios down to 0.33 in order to observe complete filling. The analysis of this plating study is currently being conducted.

Another possible method is to attach the sensor to the mold face before the plating operation is carried out. An electrically and thermally conductive silver paste (k=109 W/m-K) used in adhesive and coating applications to 1200°F has also been considered due to the ease at which trials can be conducted. Ultrasonic welding and diffusion bonding have been proposed as possible solutions. An ultrasonic welding equipment manufacturer agreed to perform an ultrasonic welding experiment to determine the feasibility of attaching a nickel strip to a copper substrate. Thus far ultrasonic welding has not proven itself an acceptable solution to the sensor attachment problem.

Fiber optic sensors are being pursued as an alternative to sensor strips. As with sensor strips, embedded fiber optic sensors have the advantage of real-time monitoring at critical locations as well as immunity to electromagnetic interference and resistance to hostile environments. Initial attempts to embed optical fibers have been met with success. Further trials with fully functioning fiber optic sensors have been planned.

Once it has been shown that a sensor can be successfully plated within the nickel layer over a copper mold, the bond between the sensor, nickel plating layer, and copper substrate can be tested. An initial check of the sensor will be performed by the mold manufacturer by immersing the copper substrate in water and applying a flame to the nickel plating layer. Any deterioration of the plating layer such as spalling or cracking will indicate a failed plating attempt.

Modeling Studies: Consequences of Gap Formation and Initial Solidification Phenomena

An incorrect plating procedure can result in an air gap forming between the sensor strip and copper substrate. In service an air gap present in the continuous casting mold can limit heat transfer and cause a localized high temperature region near the sensor. Such a temperature increase can contribute to plating layer failure or lead to the sensor spalling off. Computational methods have been utilized to quantify this behavior. This is needed in order to evaluate the maximum size of gap that would still allow performance of the sensor.

The final task will be to interpret the signals from the new sensor. One benefit will be to discover new insights into meniscus phenomena and defect formation, which arise at the meniscus. In the meantime, work to improve understanding of meniscus phenomena is proceeding at the University of Illinois using computational models, metallography, and microscope analysis of plant samples, previous laboratory experiments, and conventional temperature measurements. A new mechanism for the formation of oscillation marks has been developed, which involves freezing of the meniscus. This work is described elsewhere [1,2-5].

Eventually, sensor signals obtained online at the commercial caster will be correlated with defects in cast steel found by evaluation of the cast product. This work will have the most commercial impact. Efforts will be made to identify characteristic signals or “signatures” of the formation of particular individual defects. This will advance the technology towards the ultimate commercialization of an “expert mold”. Improving this important process even slightly has a huge potential impact in energy savings, yield savings, steel quality, and efficiency improvement, because this particular process is used to produce several hundred million tonnes of steel every year.

Discovery of New Sensor Technology

All of the project activities aimed at discovering, developing, and implementing a new technology for monitoring temperature and other phenomena in the continuous casting mold using efficient and accurate new sensors.