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PROCESS CONTROL SENSORS FOR THE STEEL INDUSTRY

Report of Workshop

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PROCESS CONTROL SENSORS FOR THE STEEL INDUSTRY

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Process Control Sensors for the Steel Industry Briefing/ Workshop Coordinating Committee

Process Control Sensors For the Steel Industry
Briefing/Workshop Coordinating Committee

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Introduction

A Briefing/Workshop on Process Control Sensors for the Steel Industry was convened and attended by 160 people on July 27-28, 1982 at the National Bureau of Standards, Gaithersburg, Maryland. It was sponsored by the American Iron and Steel Institute (AISI), the Defense Advanced Research Projects Agency (DARPA) and the National Bureau of Standards (NBS). The aim of the Briefing/Workshop was to first provide scientists and engineers in industry, universities and government with specific Process Control Sensor needs of the Steel Industry and second, to seek immediate input and future research and development involvement from a broad spectrum of disciplines to facilitate development of sensors. This report is the proceedings of the deliberations from the Workshop portion of the meeting. The material was obtained from detailed notes and summaries given to us by the Recorders and Moderators of the four different Workshop Task Groups.

The General Research Committee of the American Iron and Steel Institute has identified the development of Process Control Sensors as an area of research that would have substantial impact toward improving productivity and quality in the steel industry. On March 11, 1980, the Committee directed the establishment of a Task Group to formulate a plan of research and development relevant to "process control and sensor development" for the steel industry. The purpose of the plan was to provide a basis for discussion with appropriate organizations aimed at getting development and basic research started on projects of interest. The Task Group was established with representatives from thirteen member companies.

On January 8, 1981, the Task Group issued a draft report entitled "Steel Industry Priorities for Process Control and Sensor Development". In this report they critically evaluated sensor applications and needs across the entire steel industry, and categorized them by type of application relative to control and by their commercial and technical availablity, and then prioritized them on the basis of need, significance and interest. In the analysis, 35 steel processes were studied and 537 process control sensor needs were identified. Individual member companies were asked to rank these needs as to present availability, level of interest, and significance for current and future operations. This ranking process reduced the number of research needs to a list of 18 potential process control sensors that were considered most significant. Of these, the AISI assigned top priority to four specific sensor needs.

The four sensor needs established were:

I. Automatic Detection of Pipe and Gross Porosity in Hot Steel Billets, Blooms or Slabs
II. On-Line Inspection of Surface Defects on Hot and Cold Strip
III. Rapid In-Process Analysis of Molten Metal
IV. Rapid Measurement of Temperature Distribution Within a Solid or Solidifying Body of Hot Steel

In August 1981, AISI Task Force Units were established with the responsibility to start research work that ultimately would lead to development of each sensor. This resulted in the Briefing/Workshop reported here.

During the first day of the meeting, coordinated briefings were given on the sensor needs of the steel industry, the available technology, benefits and information pertinent to relevant research. A

Workshop/Task Group format, organized by each of the four task groups responsible for a specific sensor need, took place in the late afternoon of the first day and the morning of the second day to permit a wide range of inputs from the attendees.

Two moderators and two recorders were assigned to each Workshop Task Group. Each Task Group had previously prepared a list of questions for the Workshop and speakers had been assigned to initiate discussion on each question with a five to ten minute presentation, thus opening avenues for further deliberations. At the end of the apportioned time for each question, the Moderators summarized the conclusions and recommendations emanating from the discussion and moved onto a new subject.

Automatic Detection of Pipe and Gross Porosity in Hot Steel Billets, Blooms or Slabs

The objective is the detection of primary pipe, gross porosity and fishtailing in hot primary rolled materials and to provide a map showing such anomalies for use during cropping.

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1. What form does pipe take in ingot cast materials vs. porosity or secondary pipe? What are other characteristics of hot blooms and slabs that may influence a test for internal discontinuities?

- Primary pipe is formed at the top of an ingot due to solidification shrinkage. Its surfaces are frequently oxidized and do not weld on rolling. This pipe must be cropped from a bloom.

- Voids can also be generated by shrinkage deep within the ingot. This is termed secondary pipe. It is not exposed to oxygen and welds shut on rolling.

- Molten steel contains dissolved oxygen which combines with carbon forming CO and porous zones, often at the top of an ingot, on solidification. If the surfaces of the pores are unoxidized they weld shut on rolling. The gas content of molten steels is much less in semi-killed or killed steels compared with rimmed or mechanically capped product.

- During rolling, the outer surfaces of the slab deform more than the center, forming a defect known as mechanical pipe or fishtail. This defect has to be cropped prior to further processing.

- A sensor system must be able to identify pipe and fishtail and locate its position to within 1" in slabs up to 12" thick. It should also be capable of locating pores greater than 3/8". Inspection should take less than 30 seconds and the technique must be able to work on material at a temperature of 1900 - 2500°F.

2. What are the likely benefits and/or possible shortcomings of each "contact" method?

- With an ultrasonic sensor, elastic waves introduced into a slab or bloom are reflected from pipe and are detected as echoes that arrive back at the sensor before the echo from the backside of the slab or bloom. The echo signal may be weak, and could be obscured when the grain size is comparable with the wavelength of the elastic waves because of grain scattering. Signal to noise might be improved by working at low frequency (longer wavelength, but this reduces resolution), or by delaying inspection until after primary rolling when the coarse cast structure has been broken down.

- The most critical problem with using ultrasonic techniques is coupling a transducer (that must remain cool) to a hot steel bloom or slab. Attempts have been made to use momentary (or rolling) contact in a number of steel mills in the U.S. and abroad.

- Poor coupling efficiency, due to surface roughness, can be overcome by the application of a high pressure to the transducer. The amount of pressure required will vary with steel temperature and grade. Some denting of the surface is likely to occur but provided dents are shallow (< 1/8") they should pose no problem. Further coupling efficiency increases and vital thermal protection of the sensor (to provide mechanical reliability) can be achieved by using a water or liquid spray couplant. However, this may be detrimental to steel quality.

- The requirement that a substantial portion of the product area must be tested to both identify pipe or porosity and to determine a cropping point is not compatible with the discontinuous nature of the contact test. Using the momentary contact method, the transducer(s) (or product) need to be moved rapidly betwen pulses and a large number of pulses might be necessary. Developing a mechanical system that is reliable and rugged to provide the transducer scanning required is expected to be difficult.

3. Electromagnetic acoustic transducer (EMAT) technology seems to offer potential for noncontact testing of hot products, but present techniques require the transducer to be relatively close to the surface. What can be done to improve signal-to-noise ratios and get the transducers further from the surface? What are the fundamental limitations affecting transducer positioning? What techniques might be employed to help an EMAT survive in the hot inspection environment? Are there safety considerations if high power is involved? How does steel grade influence test sensitivity?

- The signal-to-noise ratio may be improved by: impedance matching, reducing bandwidth, increasing magnetic field strengths (to 6-10 kG), increasing the number of coil turns (but this could result in higher voltage levels) and increasing the drive current. Surface roughness decreases the efficiency. Signal averaging should also improve S:N.

- Sensitivity decrease due to lift-off from the specimen, can be compensated for by increased EMAT size, a higher drive current and a restricted bandwidth.

- The EMAT may not be as intense a source of elastic waves as say thermoelastic generation with the pulsed laser, but its sensitivity as a detector may be greater than that of a laser interferometer.

- EMATs can be used at temperatures up to 1000°F with minimal shielding. Higher temperature operation would require development of radiation shields.

- A practical system utilizing a single scanned transducer is likely to cost $100,000.

4. EMA transducers typically are not "pure-mode" devices in that both shear and longitudinal waves may be generated with various angles of incidence. Is that a serious problem? Can it be overcome in a practical inspection system?

- EMA transducers generate both longitudinal and shear waves. The theory of generation is now fairly well established and a design could be made that was optimal for a particular application. The generation of both wave types is thus not a limiting problem and it can be overcome through sensor design.

- Departure of EMA transducers from their theoretical characteristics can be caused by non-ideal magnetic field patterns. For a high temperature transducer it is likely the magnets would be pulsed electromagnets. The resulting pulsed fields would further contribute to variations in magnetic field patterns and to loss in predictability of transducer performance.

- Higher electrical resistivity of steel at elevated temperature will lower EMAT sensitivity because of decreased eddy current flow.

5. Lasers are reportedly being used for both remote generation and reception of ultrasonic signals. What are seen as the limitations of this technology in terms of power levels needed and resolution to detect small flaws in a relatively large product as is being discussed here? What are the limitations in pulsing rate and how will this affect the time required to complete testing on each bloom/slab?

- The amplitude of the elastic waves generated by a pulsed laser increases with flux. For a given flux, the amplitude decreases approximately as 1/r because the source radiates spherically. The flux required will therefore depend on:

  a. The smallest signal detectable with a detector.
  b. The size defect to be detected.
  c. The distance travelled by the elastic wave from source to defect to detector.

- For moderately sensitive detectors and large defects up to several inches within a plate a flux of 1-10 $MWcm^{-2}$ is probably sufficient. This translates into a laser pulse of 200 mJ deposited onto an area of 0.5 cm^2 in a time of 20×10^{-9}s assuming a reflection coefficient of 0.5.

- For practical applications pulsed solid state (such as Neodymium YAG or glass) or gas (such as CO_2) lasers have adequate energies. They are able to be pulsed with repetition rates of 10-20 pulses per second and their energy can be varied continuously.

- Laser interferometers are being developed in many different forms and with gradually improving sensitivity. Krautkramer* (Germany) has developed a laser interferometer that might be able to cope with the steel mill environment and because of this, remote positioning may be preferable to an EMAT detector.

- Problems that must be addressed with the laser approach are dust and water vapor in the optical path, safety, laser reliability, surface effects and engineering for implementation.

- Krautkramer has developed a laser pulsing/interferometric receiving system intended for use on hot steel. They use an 80 MW power YAG laser pulsing at 50Hz. Although no problems have been encountered with dust and water vapor in the area near the product to be tested, they stress the need to keep the system optics clean. Also problems could be encountered in laser reliability and cost due to the high power used.

*See note of disclaimer on last page.

6. To increase EMAT sensitivity, it may be useful to cool the hot surface to just below the Curie temperature. What are the implications of this technique?

- The magnetostriction effect (which only occurs below the Curie temperature) can be used to enhance the efficiency of an EMAT.

- To use this approach, the French have used water cooling to reduce surface temperatures to just below the Curie temperature (~1100°F). Such cooling could create material problems and the steel industry would probably prefer a device that operated satisfactorily between 1900-2500°F.

7. What techniques, other than those discussed, might be considered for detecting pipe or gross porosity in hot steel?

- Penetrating radiation, such as neutrons or x-rays, could be used for radiography or CAT scanning. They pose very significant safety problems however.

- General Electric (GE)* has developed a laser based acoustic emission system for detecting acoustic emission events in electric power turbine rotors. The GE system uses a split laser beam which is reconverged optically on the detection surface. Speckle patterns resulting from (a) surface roughness and (b) surface movement caused by ultrasonic vibrations are detected by a photo detector. Doppler shifts are used to detect ultrasonic signals.

- The GE system is useful on rough surfaces and could therefore be readily used on primary steel products. Detection capability is reported to be 5-10Å displacement. To put such numbers into context, the Krautkramer pulsed laser is capable of creating a 100Å displacement back wall echo at the detection surface.

- J. L. Morgan (Scientific Measurement Systems, Inc.*) described a γ tomography technique that has the potential to detect 0.02" defects through 12" steel slab/bloom in about 10 s. It would cost about $500,000 to implement. The system uses a fan beam of γ rays up to 90° wide with an array of 2 mm wide plastic scintillation counters as detectors.

*See note of disclaimer on last page.

On-Line Inspection for Surface Defects on Hot and Cold Strip

The objective is the detection, characterization and classification of surface defects on hot or cold strip for quality control during processing operations. The sensor system must:

a) Have a high speed sensing capability because strip speeds of up to 6000 fpm are possible.
b) Be capable of better defect classification than is presently available.
c) Be able to handle very large quantities of data and reduce them for on-line decision making.
d) Operate in the severe mill environment with variable production conditions.
e) Be economically justifiable, cost less than $0.1 - 0.2M per line.

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1. To what extent is it necessary to characterize defects (identify as seam or scab, length, width, depth; raised or sunken in strip) and to outline the defect boundary?

- Whether a defect is detrimental or not depends on the sheet's intended use. On-line inspection for surface imperfections must be performed early enough in the processing route to classify the product for a particular end use. Diversion of less than prime product or misdirection of incorrectly classified product directly affects product yield and steel processing costs.

- Surface imperfections must be defined and characterized before a method or equipment capable of detecting, characterizing and classifying surface imperfections can be developed.

- There are basically three classifications of surface defect:

  a) Linear
  b) Area
  c) Miscellaneous and intermediary

  Linear defects are narrow and long, the width dimension being as small as 0.03" and the length extending several feet in some cases. Examples would be scratches, roll marks and seams. Area defects may be either single or occur in groups of the same type of imperfection. A single defect may be as small as 0.03" in diameter, but groups may extend over several square inches of surface or even several square feet. Examples would be slivers, laps, scabs, holes and scale. Miscellaneous and intermediary types of defects include those caused by mechanical damage, edge defects (cracked, wavy, damaged and breaks) and gouges. In general, although they are gross defects, their detection may be complicated by their location.

- It is desirable to detect defects as early, during processing, as possible consistent with accessibility to the sheet. The lower limit for detection should be about 0.03", but may be limited by factors such as sheet velocity.

- Classification of defects should distinguish anomalies (e.g. liquid drops) from true defects. Pattern recognition may be used to develop decision-making rules and deduction of defect origin for feedback control of processing variables. At the very least, a system should give a go, no-go decision.

2. How well must the defect be located?

- Briefly, a desirable requirement would be to locate a 30 mil defect to ± 1/4" in the width direction and ± 12" in the length direction on a 5 mile coil processed at 6000 feet per minute. The sheet width could be 20-80" and thickness 1/4" (hot rolled) to 0.006" (cold rolled).

- Defect location is important in:

  a) Slitting
  b) Diversion of defective strip portions
  c) Correction of processing to eliminate future defects (e.g. roll defects)

  In practice it would be desirable to locate all defects but it is likely only a part of the information would be used for each particular operation.

- Consumers currently tend to inspect the first 150 feet of rolled sheet coil and reject the entire roll if this front end is defective enough.

3. How important is it that inspection results be obtained in real-time?

- The advantages of real-time inspection are:

  a) Diversion of products with unacceptable defect concentrations can be used to avoid subsequent processing costs and minimize bottle necks.
  b) Implementation of immediate corrective actions to processing procedures to eliminate further defects.
  c) Reinspection either manually or at a slow speed to accurately characterize defects.
  d) An aid to production scheduling so costly inventories can be kept to a minimum.

- It is imperative that inspection results be in real-time to allow immediate decision making by the mill operator.

- If signal processing speed is a limiting factor in providing real-time information, then it would be desirable that some immediate indication of a defect be provided to the operator, followed, up to a few minutes later, with the detailed characterization (type, size, location,...). Finally, a hard-copy of the inspection results is certainly required, though not in real-time.

- The minimum information for decision making should be supplied to a mill operator. His experience may enable quicker judgements to be made than would be made by relying entirely on computer-based decisions. It is not clear what information should be given. Perhaps a percentage of the width with defects, or some visual display. The latter might be particluarly useful since one of the most effective current methods is to use the eye of an operator and some TV display.

- The sensor system can be verified and calibrated by running a standard sheet of known defects through the system.

4. What constitutes an undesirable defect? How do you distinguish it from conditions that are not detrimental?

- There are no industry-wide standards and one of the major problems with current process NDE is to distinguish detrimental and harmless defects. This categorization depends both on the ultimate application for sheet product and the economics of product over-rejection.

- Harmless defects include drops of water, light stains, grease and residual rolling lubricant. They are difficult to distinguish between detrimental and harmful defects at present. When an imperfection becomes severe enough to degrade the end use of the product, then it is considered a defect. Since the defect criterion is one of the product suitability, it is product dependent. Therefore, a condition which may be a defect on cold rolled strip may not be a defect on hot rolled material.

- Novel NDE approaches worth considering for defect characterization are ultrasonics and acoustic emission utilizing EMAT's or laser interferometers. Optical methods (particularly laser scanning) are probably the most effective presently. Some hybrid approach may give the best defect categorization ultimately, particularly in combination with adaptive learning.

5. Can inspection locations be limited in order to minimize environmental, temperature, speed, etc. requirements?

- Inspection locations can be limited to minimize environmental, temperature, speed and stress requirements. Many, if not most, of the defects probably originate in the melt and during solidification. It would be highly beneficial to detect them at this point. Also, since strip speed increases as it passes through the mill, there might be both economic (less wasted processing) and practical advantages to early location of defects.

- Probably the most desirable location from an economic standpoint is at the temper mill. This is the last operation for uncoated low carbon steel and is the last opportunity to prevent defects from entering the customer's plant. There are environmental problems associated with this line: very high line speed (e.g. 30 m per second), limited space and danger from wrecks. However, because of the economic implications, this is a <u>must</u> location for some kind of inspection device.

6. Are separate inspection techniques or systems required to evaluate the different surfaces encountered in steel processing (such as dull, bright or roughness variation)?

- Background reflectivity conditions represent a serious consideration in the design of an optimum surface inspection system. Dull surfaces scatter light in a diffuse or non-specular manner. Polished surfaces however, give specular reflection. These result in different intensity light source requirements and variations in the optimal angle of observation.

- Alternative techniques suoh as holography might be difficult to implement because the sheet is moving, vibrates and is in an extreme environment. The ultrasonic method utilizing scanning lasers and interferometric detectors or acoustic emission also must overcome these problems.

7. Is inspection of both surfaces of the strip necessary?

- Generally speaking, inspection on both sides of the strip is desirable. However ultimately the question is determined by accessibility, economics and ultimate product use.

8. What is the importance of economics in considering an inspection system?

- NDE systems in rolling mills have to pay for themselves. They do this by minimizing the amount of material that must be reprocessed and the elimination of excess trimming. A third consideration is customer claims and buyer confidence.

- It is impossible to ascertain the loss due to creation of poor business relations caused by the selling of a product which is anything but "zero defect". Typical penalties of $60,000 per month are encountered for cold rolled product shipped with surface defects and slivers. It has been estimated that $50 million in annual savings (through increased productivity and reduced cost) could result if suitable sensors were developed.

- Consider an example problem occurring at all tandem mills. Specifically, the surface inspection system is to detect repetitive mill-produced surface defects. These flaws will occur for a time with some periodicity related to roll circumference. The surface inspection system logic will indicate the stand containing the damaged roll to facilitate the elimination of the problem. The alternative to this automatic detector is to take every third coil leaving the mill, unwrap the coil, and visually inspect for repetitive defects. With this manual inspection, as many as three coils are affected whenever a mill-produced defect is found.

  A principal example of financial rewards by eliminating costly further processing of defective material is surface inspection at the exit of a pickle line. This example is based upon typical data taken during a six-month period in the year 1967. Obviously, the savings based upon present operating cost is significantly higher. The analysis is restricted to the savings obtained by diverting coils from a tinplate product to a galvanized product due to surface imperfections.

Coils are visually inspected on both surfaces with the assistance of mirrors as they leave the pickle line. This visual inspection is somewhat effective with regard to gross surface defects. However, present-day pickle line speeds make it difficult to detect minor surface defects which may also be indicative of major sub-surface defects.

Coils which are rejected for defects at pickle line inspection are diverted to galvanized orders and scheduled through the proper tandem cold rolling mills to achieve the desired galvanized gauges. Experience has shown that coils with surface defects which would result in unacceptable tinplate products produce acceptable prime galvanized coils or sheets.

The difficulties mentioned with regard to line speed and surface defects result in rejections at inspection at the end of the electroplater. "Lines" and "slivers" produce unacceptable surface quality and result in the rejection of a substantial number of coils and units.

For the six-month period of 1967, an average of 1,000 tons per month of tinplate products were rejected for steel defects. This tonnage would have been diverted at the pickle line to prime galvanized coils if these defects had been detected.

Savings of $100,000 per month would have accrued from:

a) The cost differential between processing these coils through the tin line versus the galvanizing line.

b) The selling price differential between galvanized prime coils and reject tinplate.

c) Profit on additional yield from the tin line by replacing the diverted coils with prime tinplate coils.

An additional $25,000 per month from reductions in lost time and roll shop costs would have brought the total potential savings to $125,000 per month.

Rapid In-Process Analysis of Molten Metal

The objective is development of a system for the rapid, in-process chemical analysis of molten iron and steel for compositional control during operations such as: refining in BOF vessels, and ladles, melting in elecric furnaces and casting. Elements to be analyzed include carbon, manganese, phosphorous, sulfur, aluminum, silicon, copper, nickel and chromium. When developed, the instrumentation could be used to:

- Provide continuous iron composition during blast furnace casting.
- Provide rapid analysis of the steel bath during the refining process.
- Monitor sulfur removal and avoid overtreatment during desulfurization of liquid iron and steel.
- Assure meeting requirements for ladle treatment processes.
- Optimize trim additions in the ladle.
- Make ladle tests while ingot teeming.
- Monitor the composition of metal going into the continuous caster.
- Optimize alloy additions in vacuum degassing.

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1. What restraints are imposed by the steel making environment upon in-process chemical analysis?

- The interval between analyses during compositional adjustment ideally should be about one minute. This could be most critical for carbon adjustment toward the end of an oxygen blow using the BOF technique.

- The analysis must be made in the hostile environment of a turbulent molten steel pool where temperatures of 3500-3800°F are encountered. If some kind of probe is used, it must be efficiently cooled.

- Large concentration gradients can occur in the melt. The technique should be able to account for these.

- The "off-gas" chemical analysis technique has already been demonstrated inadequate for this problem.

2. What instrumental designs are required for a sensor to survive high temperatures and hostile environments?

- Four basic approaches are available:

  1. Transient techniques which take samples (for off-line analysis) using cheap, destructable probes.
  2. Active probe cooling using water or gas.
  3. Thermal insulation of the probe.
  4. The use of ceramic probes able to withstand high temperature.

- Disposable cardboard shielded probes are in use today and give reasonable performance. Disposable probes should cost $15-20 each to ensure cost effectiveness.

- There may be problems of poor thermal shock resistance with ceramic probes although a water-cooled steel probe with alumina lining is currently being evaluated at Lehigh University.

- The least hostile environment where a chemical analysis sensor would be useful is ladle metallurgy process control and there might be some merit in tackling this problem first.

3. How can a molten steel bath be analyzed by emission spectrochemical methods?

- Because of the extremely hostile, corrosive, high temperature and mechanically violent environment, and because in the BOF slag is emulsified with the steel, sampling is a fundamental problem that must be addressed.

- The spark discharge technique may be difficult to implement directly into the furnace due to likely variations of the spark-source gap and optical component fragility.

- Generation and transport of an aerosol is a more encouraging approach. Aerosols representative of bulk composition have been produced and transported as far as 100 ft. A problem here, however, is the time lag in making an analysis, particularly critical for the BOF technique.

- Analysis precision depends upon effective elimination of slag contributions to spectra (less of a problem for ladle composition control), careful instrument calibration and the development of predictive models to minimize time lag effects.

4. Are nuclear techniques useful for analyzing molten metal during processing: What are their advantages and limitations?

- A great variety of nuclear techniques are now available for determining the concentration of elements such as C, Mn, P, S, Si, etc. A combination of these could, in principle, be used to deduce the composition of a sample of steel.

- Analysis, using existing methods, would take about 5-10 minutes. This is controlled by counting statistics and therefore depends upon source intensity and element concentration.

- Transportable radiation sources, such as Californium, are available, though expensive. Detectors, such as cryogenically cooled Ge, each cost upwards of $50,000.

- These techniques pose a significant safety hazard. It is unclear if the precautions needed to guarantee safety would exclude application of these methods.

5. What are the possible applications of laser technology to in-process analysis of molten metal?

- A short duration (10-20 ns) laser pulse with an intensity of 10^9-10^{10} Wcm^{-2} will evaporate (ablate) the surface of a metal. The vaporized metal could then be analyzed.

- Further laser radiation of the metal vapor could excite x-ray emissions whose energy are characteristic of the elemental composition.

- High background, near a molten metal surface, would preclude direct analysis, but Ar or He streams could be used to transport the vapor to a more suitable analysis location.

- An exploratory study to establish feasibility is required. Additional problems to be addressed include the susceptibility of laser optical components to vibration and the safety hazard associated with class IV laser systems.

Rapid Measurement of Temperature Distribution within a Solid or Solidifying Body of Hot Steel

The objective is the development of a system for the rapid, direct measurement of temperature and temperature distribution within a solid or solidifying body of hot steel. The sensor should ultimately be capable of measurements in the hostile environments associated with a variety of production facilities such as continuous casters, reheat furnaces, ingot soaking pits and annealing furnaces.

The "ideal" sensor would measure temperature within ±10 C over a temperature range of 500 to 1350 C without the need to physically contact the sample. It should also take only a few seconds to provide the temperature distribution and be insensitive to the presence of combustion gas products or of nearby sources of heat greater than the temperature being measured. Sensors for "specific" applications might not have to match all the specifications of the "ideal" sensor.

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1. How might the internal temperature distribution sensor be applied in various steel processing operations?

- During continuous casting, liquid metal breakouts can arise should the partially solidified stand be withdrawn too rapidly. Normal variations in a number of other casting parameters make low casting speeds necessary. Casting problems can also occur due to irregular solidification within a strand. If sensors were available to measure temperature distribution within the solidifying strand, it would enable the shell thickness and heat removal rate to be continuously monitored and used for feedback control. The sensors would have to withstand an extremely hostile environment with hot steam, high temperature and occasional sprays of molten steel.

- In a reheat furnace, steel slabs with unknown initial temperature states are heated for rolling. Extended soaking to insure a uniform heat condition is wasteful of time and energy. A sensor to measure temperature distributions before, during and after heating would provide needed information permitting savings in both areas. A contacting sensor must survive the hostile environment of the furnace and be insenstitive to oxide layers. A noncontacting sensor must additionally be unaffected by dust and flames within the furnace.

- The spatial resolution needed will depend upon the particular application. For control of continuous casting, a resolution of ±2 mm and ±10 C would be advantageous, whereas for a reheat furnace, a reading of the minimum internal temperature could be sufficient.

- The needed frequency with which temperature distribution is measured (temporal resolution) reflects the application. In continuous casting, a continuous observation of temperature distribution is desirable; in the reheat furnace, periodic measurements would be sufficient.

- The use of computer models to predict temperature distributions have been only partially successful. Direct measurement of temperature distribution, even at a coarse resolution, would greatly aid in adjusting heating models to changes in the heating situation.

2. What are the capabilities and limitations of conventional methods for measuring the temperature of solids at their surfaces and within their interior?

- Thermocouples have been used both for surface and limited interior temperature measurement. They have unsatisfactory resolution, are mechanically fragile and require elaborate precautions to survive the reheat furnace environment.

- The absence of a well-defined set of emissivities for hot steels is one problem with radiation thermometry. The emissivity of clean steel is typically 0.4 - 0.5 depending upon composition. This rapidly increases to 0.8 when a thin oxide layer forms. Further increases with increasing thickness are then small until surface roughness develops when the emissivity increases towards 0.95.

- Loose surface scale poses an additional problem because of its poor thermal coupling to the substrate. Thus, it undercools or superheats during cooling/heating treatments leading to gross error in deduced substrate (surface) temperature.

- Reflected radiation from furnace walls and atmospheric absorption associated with combustion fuels are additional sources of inaccuracy with the radiation thermometry technique.

- Radiation thermometry only measures surface temperature. However, it may be possible to measure the rate of change of surface temperature to deduce a thermal profile. In essence this is the solution of the thermal diffusion equation using the surface temperature, and rate of change of temperature as boundary conditions. Unambiguous solutions probably also require the (unknown) thermal history.

3. To what extent can these techniques, in combination with computer models, be used to infer temperature?

- Experience has indicated models based upon physical insight give the best results.

- Models alone, however, are not sufficient due to lack of knowledge of the extent of changes in heating variables. A more powerful approach is to combine computer models with actual measurements.

- The combined approach could be improved with better high temperature (> 1800 F) thermal property data (thermal conduction, heat capacity and heat of fusion), improved values for heat transfer coefficients and more accurate surface temperature measurements.

- The computer models now being used are constructed from a set of assumptions and often supported by few actual temperature measurements. Using sensors, the fewer the assumptions and the better will be the precision of predictive computations. Even a sensor capable of average temperature measurement could provide a useful check on model predictions.

4. What principle phenomena and/or material properties of steel undergo a change with temperature? What techniques are available for monitoring these changes?

- While many physical properties are temperature dependent, it is worthwhile to concentrate upon those for which nondestructive, hopefully noncontacting measurements in hostile environments can be made. Three basic phenomena can be considered:

  a. Change of elastic constants
  b. Thermal expansion
  c. Change of phonon distribution

- Elastic constant changes can be measured by monitoring ultrasonic velocity. This could give the surface temperature (longitudinal/transverse waves) and the temperature field using computerized tomography.

- Ultrasonic velocity can, in the laboratory at least, be measured using noncontacting laser generation/detection and EMAT techniques. The effect of surface oxide layers is one problem that must be addressed if these approaches were attempted in the mill.

- Thermal expansions can be measured directly as lattice parameter changes using X-rays (or laser interferometry or holography) or indirectly, as density changes, using γ or neutron radiography, to give average temperature.

- Changes in phonon distribution could possibly be detected by measuring the energy distribution of thermal neutrons that have traversed a hot steel body (provided the capture cross section is not too high) or by measurement of electrical resistivity using eddy current methods, to give average temperature.

5. What are the relative merits and prospects for the various technologies that have been considered?

- Acoustic velocity measurements are advantageous for the measurement of temperature profile because of the penetrating nature of elastic waves, the ability to use tomography to deduce temperature distributions and the availability of EMATs and laser techniques to generate and detect the elastic waves.

- Further work on the acoustic velocity technique is required to provide basic information about velocity changes due to microstructure, preferred orientation and residual stress as a function of temperature.

- Unresolved issues are the durability of acoustic velocity sensors, their resolution due to scattering by microstructure and scale and the influence of phase transformations ($\gamma \leftrightarrow \alpha$).

- Thermal expansion coefficients can be measured by laser techniques with considerable precision and this could provide a noncontacting rapid method for deducing average temperature. Density determinations using x or γ-ray radiography suffers from severe safety hazards.

- Electrical conductivity techniques are basically near surface techniques (within a few inches). Multifrequency techniques have been used to deduce profiles down to 4" and have been applied to continuous casting.

- At high temperatures (above 1500 C), resistivity is, in the main, dominated by phonon scattering and compositional differences are not too important until one gets to very high alloy concentrations (of the order to 30%). At lower temperatures, resistivity is very sensitive to microstructure and, indeed, has been used to monitor precipitation of intermetallic phases (e.g., the sensitization of austenitic stainless steels can be observed).

- If only the position of a liquid-solid interface is required (and no temperature data), for example, during continuous casting, pulse echo ultrasonics and γ radiography show much promise.

- Battelle Northwest, under DoE funding, has reviewed various approaches to measurement of thermal state. Because they were interpreted in a longer term basic study that would have generic benefits, they have recommended the laser generation of ultrasound coupled with computer tomography as the best choice for a temperature distribution sensor.

6. What other applications outside the steel industry are there for an internal temperature sensor?

- The most obvious application might be to the processing of nonferrous alloys. Other applications might be the manufacture of cement, semiconductor crystal growth, hot isostatic pressing and, perhaps, during the manufacture of glass. However, in none of these applications is the sensor likely to make such a revolutionary impact as in the steel industry.

7. What steps should be taken to stimulate the development of a sensor to measure internal temperature?

- There is a clear financial incentive (productivity improvements valued at $275 million annually) for the development of a thermal distribution sensor. Laboratory studies are required to establish correlations between physical properties and temperature and to demonstrate the feasibility of internal temperature measurement.

- AISI seeks to develop a research program and therefore solicits research proposals. These should be no more than two pages in length and contain brief statements, on the approach to the problem, background information, work proposed, time required and funding needs. They should be sent to AISI headquarters in Washington to the attention of W. E. Dennis.

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