Sponsor TBD Report No.

AISI/DOE ADVANCED PROCESS CONTROL PROGRAM

FINAL REPORT

Vol. 6 of 6: TEMPERATURE MEASUREMENT OF GALVANNEAL STEEL

4/1/94-4/30/97

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July, 1999

Work performed under Cooperative Agreement No. DE-FC07 - 93ID13205

Prepared by
American Iron and Steel Institute
Advanced Process Control Program
For
US Department of Energy

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FOREWORD

The authors wish to thank all those who in the past and up to the present have supported this project. Lawrence Kavanaugh and Joseph Vehec, among others at the American Iron and Steel Institute, supported the project from many angles, not only with respect to the financial aspects but including crucial managerial and technical assistance as well. Another key factor in the success of this project was the opportunity to perform field-testing on the galvaneal line at National Steel. To move instrumentation from the laboratory to the application requires “real world” testing. The authors are also grateful to National Steel for providing the test site and the requisite technical assistance to make the testing of the device possible. Bill Obenchain (now with AISI) and others at DOE’s Office of Industrial Technology also played critical roles in our success.

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EXECUTIVE SUMMARY

This report describes the successful completion of a project entitled "Temperature Measurement of Galvanneal Steel". This project was a part of the American Iron and Steel Institute's (AISI) Advanced Process Control Program. Jointly funded by the Department of Energy (DOE) and fifteen AISI member companies, Advanced Process Control Program was aimed at developing new sensor and control system technology for processes from steelmaking through finishing. The fifteen companies are Acme, Bethlehem, Dofasco, Geneva, Georgetown, Inland, IPSCO, LTV, Lukens, National, Rouge, Stelco, Timken, U. S. Steel, and Weirton. In this particular project, the research partners were the U. S. Department of Energy's Oak Ridge National Laboratory and the University of Tennessee; National Steel Corporation was the steel company sponsor.

This three-year project used phosphor thermography, an outgrowth of uranium enrichment research at Oak Ridge facilities. The goal was to develop an on-line tool for accurate in-process measurement of steel surface temperature during the galvannealing operation. Temperature is the controlling factor regarding the distribution of iron and zinc in the galvanneal strip coating, which in turn determines the desired product properties.

The most important features of this new online system are stated below:

1. The device enables thermometry between 450 and 700 C (about 800 to 1300 F) by exploiting the temperature-dependence of ultraviolet excited phosphor fluorescence.
2. It is emissivity independent, allowing for reliable and accurate temperature determination.
3. The phosphor layer has no detrimental impact on product quality.
The calibration is performed with primary standards and will not drift because it is:
 - time based - therefore there is no analog drift,
 - controlled by a crystal clock - 0.001% maximum error,
 - based on a chemically stable phosphor material.
4. The device utilizes an off-the-shelf standard IBM/ISA system with graphical user interface.
5. The device uses custom-designed large field-of-view confocal optics, which accommodate the movement of the galvanneal sheet.
6. The control system is AISI-proprietary, consisting of:
 - Custom data acquisition board
 - Custom Software
 - LabView™ graphical user interface

Bailey Engineers Inc., has been selected by the AISI to commercialize this technology.

There are several potential extensions of this technology:

Steel

- Slab heating
- Melt temperature
- Roller temperatures

Other Materials

- Galvalume
- Ceramic

Other Industries

- Aircraft components
- Automobile components
- Petroleum
- Pulp and Paper
- Glass

1.0 INTRODUCTION

1.1 Rationale

This report describes a device for in-process measurement and control of galvaneal steel strip temperatures. The device operates independent of surface emissivity. Hot dip galvanealed steel has been extensively used in automotive industry because its weldability, paintability and cosmetic corrosion resistance after painting are superior to pure zinc coated steel. Galvannealing process conditions have to be controlled tightly in order to produce high quality products. Galvannealing temperature is one of the important process parameters, which affect product quality greatly.

The prototype galvaneal temperature system described here has demonstrated the capability for measuring galvaneal steel temperature through several production line trials at National Steel's plant in Portage, IN.

This system will help to control galvaneal temperature profile for new products developed in laboratory to production line directly. Furthermore, this system provides an opportunity for closed-loop control on galvannealing process, i.e. using a temperature signal to control galvannealing furnace power automatically. This closed-loop control will improve the consistency of product quality and productivity further.

1.2 Technical Approach

Thermographic phosphors are relatively inert, doped ceramics which emit light with a distinctive spectral distribution when suitably excited by an energy source such as an electron beam, x-ray source, or ultraviolet light. If the source is pulsed, then the fluorescence will persist for a characteristic duration. The fluorescence properties change with temperature. Different spectral components from the same material may even exhibit different temperature responses. These changes are independent of the emissivity of the surface to which the fluorescing material is attached.

The brightness of phosphor decreases exponentially in time and the time required to fall by $1/e$ is termed the decay time or lifetime. This is illustrated in Figure 1 for a representative phosphor where the decrease is seen to be more rapid at the higher temperature. Provided a single exponential describes the decay and there are no chemical reactions altering the phosphor, the decay time is a single-valued function of temperature over a wide and useful range. The decay-time based approach was chosen for this application; although, there are other fluorescence properties that may be exploited to ascertain temperature (e.g. emission intensity). Decay rate measurements tend to retain calibration better than intensity-based approaches (1,2,3).

A collaboration of Department of Energy laboratories, (ORNL, LANL, and EG&G Energy

Figure 1. Time dependence of $\text{La}_2\text{O}_2\text{S: Eu}$ at 65 and 75 °F.

Measurements - now Bechtel Nevada Special Technologies Laboratory) have utilized and developed the technique for a wide variety of low, ambient, and high temperature applications as reported at this conference in recent years (4). Surfaces of motors, centrifuges, and turbines, for example, have been diagnosed by this method (4,5,6). In addition to the advantage of non reliance on emissivity, the method has the advantage that it is noncontact; i.e. measurements can be made from a distance.

Infrared pyrometry is sometimes used as a temperature indicator for galvanneal processing. However, the accuracy of pyrometry depends on the emissivity of a surface. Because, the emissivity of the molten layer of zinc on the sheet varies rapidly during the process, pyrometry is subject to corresponding uncertainty and unreliability.

Figure 2 illustrates how this method is configured for galvanneal thermometry. A deposition apparatus delivers a small amount of phosphor to the surface. When the phosphor spot moves up to the field-of-view of the collection optics (called the optics head), a laser fires a pulse of light into a large core (1-mm) optical fiber. It delivers the light to the phosphor spot on the galvanneal surface. A lens system accomplishes the focusing to the surface. The phosphor absorbs the ultraviolet light and re-emits the energy at a later time as visible fluorescence. The duration, also called the decay time, is temperature dependent. The lens system collects the fluorescence and images it onto a fiberoptic bundle. The light is conveyed to a filter, which transmits only the desired color to the detector (photomultiplier). A data acquisition system converts the detector signal to temperature. The data acquisition computer also produces control signals, triggering the deposition system and the laser.

The advantages of high temperature measurements that incorporate thermographic phosphor techniques are many. Since the method can be performed remotely, it is useful in hazardous, noisy, and explosive environments. Optical temperature measurements of this kind are also immune to electrical interference and have a wide sensing range based on the selection of the proper phosphor. With current state-of-the-art electronic equipment, measurements can be made at a rate of 5000 per second, if desired, for process monitoring and control.

Figure 2. System Schematic.

2.0 DEVELOPMENT OF THE SYSTEM

2.1 Phosphor Science and Research

A variety of phosphor materials were selected and tested for the specified galvanneal line temperature range of 450 to 700 C (about 800 to 1300 F). In the end, two materials performed well enough to be used in field-testing described later in this report. These were magnesium fluorogermanate doped with manganese and yttrium oxide doped with europium. Longer decay times and better performance at the low end of the temperature range characterized the former. Careful determinations of decay time versus temperature were performed in the lab to obtain calibration curves.

A variety of light sources may be used to excite fluorescence from either of these two phosphors. A portable nitrogen laser proved viable for this device. The output ranges from approximately 0.1 to 0.3 mJ from 0 to 50 Hz.

Thermal modeling established that a thin phosphor layer would equilibrate with the galvanneal top surface. Calculations determined the time required for the phosphor to come to temperature once deposited on the galvanneal strip. Published values were used for the thermal conductivity, density, and specific heat of europium-doped yttrium oxide and it was assumed that these values are comparable to magnesium fluorogermanate. The table depicts the results.

Table 1. Thermal Modeling Results

phosphor thickness	initial temperature	steel temperature	time to get within 5C	time to get within 2 C
250 μm	30 C	600 C	11 ms	25 ms
50 μm	30 C	600 C	0.6 ms	0.75 ms

Notice that even for the rather unreasonable and unrealistic thickness of 250 μm , the time-to-temperature is rapid. The phosphor thickness is estimated to be less than 50 μm , hence the time for the phosphor to equilibrate should be less than a millisecond.

National Steel and Oak Ridge project teams jointly explored environmental issues early in the project. National Steel examined the wastewater contamination aspect as well as issues associated with introducing a new chemical material into the manufacturing environment; Oak Ridge examined those issues associated with personal exposure to the phosphor material.

National Steel Findings:

1) The introduction of rare earth doped ceramic materials pose no wastewater problems in the amounts intended to be used. Furthermore, the phosphor materials are not water soluble and therefore would simply constitute a solid particulate, non-reactive constituent which would more than likely accumulate in the quench bath.

2) With regard to introduction of the phosphor material into the manufacturing environment; as long as Material Safety Data Sheets are provided to safety, medical, and plant protection personnel and the proper approvals are obtained through the Product Approval System the introduction of the phosphor material should be permissible.

Oak Ridge Findings:

1) The Oak Ridge project team pulled the Material Safety Data Sheets (MSDS) for a variety of the phosphors. All MSDS sheets revealed similar information with respect to hazard, toxicity, and reactivity characteristics. The only significant concern lies in the phosphor materials potential for inhalation. All phosphor materials are fine white powders and could be easily inhaled if not cared for properly. If inhaled, the phosphor may cause nasal or respiratory irritation but oral toxicity is expected to be low.

2) These materials are insoluble, non-reactive, non-volatile, and non-flammable owing to the fact that they are inert ceramic based materials with extremely high vapor pressures and melting points.

2.2 Optics

The optics for the final embodiment evolved during the course of the development as experience and testing results accumulated. The first test involved an approach where the detector was within a few feet of the induction heaters. This led to a large amount of radio frequency interference (RFI) superimposed on the fluorescence signal. This is seen in Figure 3. An approximate decay time and, therefore, temperature can be determined from such data with sufficient analytical and computational effort. However, the RFI was completely eliminated by moving the light source and detector some distance away from the measurement zone and by accessing the zone with fiber optics. This is shown in Figure 4. The sharp spike at the beginning of the decay curve is due, in this case, to some leakage of laser light ($< 1 \mu\text{s}$) to the detector. The data acquisition system described later ignores this part of the decay curve in determining the lifetime of the fluorescence.

What is termed the optics head is shown in the photo of Figure 5. The items are mounted in an anodized aluminum housing. Cooling air is delivered via Teflon™ tubing seen in the photo. Figures 6a and 6b are drawings of the optical system. The laser light is delivered from the remotely located nitrogen laser via a single optical fiber. Inside the optics head the light is reflected from a mirror and directed to a dichroic mirror, which directs the beam through a lens to the galvanneal surface. The fluorescence from the moving phosphor spot is captured by the same lens and passed through the dichroic mirror. Two lenses focus the fluorescence into a second optical fiber, which conveys the signal to a remote detector. These two lenses comprise a confocal optical system with a large field-of-view (FOV) and a large depth-of-field (DOF). Because the fluorescing spot moves significantly as it is being observed, the large FOV prevents vignetting of the signal. This would lead to an error in the lifetime and, hence, temperature determination. The galvanneal sheet will vary in its distance from the optical head depending on operational conditions. The large DOF assures adequate signal over a wide range of this motion.

Figure 3. Fluorescence signal with RFI.

Figure 4. Fluorescence signal with fiberoptics.

Figure 5. Optical Head Assembly

Figure 6a. Ray tracing detail laser light emerging from fiber through focusing lens, beamsplitter, aperture to the galvanneal sheet.

Figure 6b. Ray tracing detail of optical path from galvanneal sheet through beamsplitter and lenses to return optical fiber.

2.3 Front End Electronics and Processing

The overall system is designed in such a way that the data acquisition system 1) controls and synchronizes the thermal phosphor deposition equipment and laser firing, 2) captures the returned light signal with a photomultiplier tube, 3) calculates temperature, and 4) provides appropriate signals for control of the process. The system is based upon an embedded computer system with associated peripherals for digitizing and processing the data and providing the output control signals. Figure 7 shows a schematic of the electrical and optical connections. The photomultiplier (PMT) in the figure converts the optical signal to its electrical analog. Figure 8 is a photograph of this rack-mountable PC. Figure 9 shows the back view of the computer as well as how the PMT is mounted to the back of the PC and the fiber connection is made.

The PMT output connects to a custom printed-circuit board for signal conditioning and interfacing. The board, shown in Figure 10, complies with the industry-standard architecture (IBM PC-compatible) board specifications and resides in the backplane of an industrial-duty PC. The custom board contains:

1. power-conditioning and signal-conditioning circuits for the photomultiplier tube,
2. timing circuitry for firing the laser, operating the powder deposition system and synchronizing data transfer with the data acquisition board, and
3. an analog output for the industry standard 4-to-20 milliamp current loop output.

A simple interface box connects the logic-level output from the custom board to the 120 VAC solenoids on the powder deposition subsystem. Power for the on-board electronics is derived from the power available on the industry-standard architecture (ISA) backplane connection. On-board power converters and regulators are used to condition the power as needed by the remainder of the circuitry. Figure 11 is a view inside the data acquisition computer.

An erasable, programmable logic device (EPLD) performs the majority of the digital decoding and processing required to identify pertinent system commands appearing on the PC backplane and convert them into the signal required by system components external to this board.

Connectors are provided for PMT power, sensitivity control, and output signal. The PMT current output is converted to a voltage signal by passing the current through a 50 ohm resistor. A fast operational amplifier boosts the resulting voltage waveform with jumper selectable gains for 20, 200, or 2,000. The amplifier output is available on the board-mounting bracket for use (normally) by the system data acquisition card. PMT sensitivities of approximately 100 A/W, 1000 A/W, or 10000 A/W are jumper selectable. (The PMT, for optimum speed and signal-to-noise performance, is normally operated at its maximum sensitivity. The amplifier gain is then set to present near-full-scale inputs to the data acquisition card.)

Once set up appropriately for a particular installation, no adjustments to or reconfiguration of the

Figure 7. Signal conditioning and interface board.

Figure 8. Phosphor Thermometry Control Computer.

ORNL-DWG 97-2039 EFG

Figure 9. Back View of Control Computer.

Figure 10. ORNL-designed and fabricated and fabricated control board.

Figure 11. Internal View of Controlling Computer.

signal conditioning and interface board is required.

2.4 Phosphor Deposition Apparatus

The powder deposition device is an automatic air-actuated spray gun. A block diagram is shown in Figure 12. Figure 13 is a three-dimensional view as it is mounted inside its housing. Figure 14 shows the device mounted and aimed at galvaneal sheet for one of the test runs. The spray gun is composed of three assemblies: the fluid body, the cylinder assembly, and the multiple head assembly. The fluid body assembly consists of a bore into which powder is gravity fed. The bore is sealed by a spring-loaded needle that plugs the nozzle of a metal bellows piston, which is attached to the needle in the bore. On the back of the cylinder assembly is a dial which adjusts the distance the needle can retract. To operate the spray gun, air pressure is applied to the gun.

The powder deposition system consists of the automatic spray gun and peripheral equipment. This peripheral equipment includes a pneumatic vibrator, which provides agitation of the spray assembly to assist the gravity feed of powder. Solenoid valves control the compressed air supplies. One solenoid valve turns the air supply to the vibrator on and off. The other solenoid controls the automatic spray gun. Two pressure regulators regulate supply air pressure. These components are mounted in a stainless steel box approximately 6 inches wide, 9 inches high, and 15 inches deep. Two pressure gauges are mounted external to the box to provide a visual indication of both the pressure delivered to the spray gun and the pressure supplied to the vibrator. Interfaces to the box are two 1/4" MNPT fittings for compressed air, and two amphenol electrical connections for solenoid valve actuation.

The motive compressed air pressure is used to open the needle valve in the spray gun and propel powder to the strip. The operating pressure range is between 30 psi and 60 psi. Pressures in excess of 60 psi may result in material being driven back into the piston cylinder. Accumulation of powder in this area will impede the operation of the bellows piston and will result in impaired operability of the spray system. If the pressure is set too low, an inadequate quantity of powder will be deposited per spray. Also, at lower pressures, the force propelling powder to the strip surface will be less, therefore random air turbulence in the vicinity of the strip will have a more pronounced affect on the distribution of powder.

Figure 12. Phosphor Deposition System.

Figure 13. View inside Container.

Figure 14. Photograph of phosphor deposition device installed for test.

Material feed control dial settings should generally be in the range of 3 to 5 turns. A lower material feed control dial setting produces a smaller and more consistently shaped spot, however misalignment may necessitate production of larger spots. A higher setting produces a larger spot, but its shape is not as consistently reproduced from puff to puff.

The powder gun should be mounted so that the nozzle is located within 4 to 6 inches of the strip. The position of the nozzle relative to the strip affects the size of the resulting spot. The farther the gun is from the strip, the more widely the powder is distributed resulting in a larger spot. However, the random turbulence in the vicinity of the strip has the tendency to blow the powder around.

2.5 System Integration and Field Testing

Several field tests were conducted during the course of the project at the National Steel's Midwest Division facility in Portage, IN. The first, early stage test involved a laboratory optical breadboard system, a nitrogen laser, and laboratory data acquisition equipment. As noted previously in this report, the test revealed that large radio frequency interference (RFI) occurs if the detection apparatus and long electrical cables are in the vicinity of the induction furnaces. This indicated the need to use long optical fiber, on the order of 30 feet or more, to remove the detector and computer from the immediate locale. The test indicated the signal levels attainable for the nitrogen laser and gave the team important experience in setting up the equipment and working in the environment.

The second field test utilized the first prototype of the optics and a LabView™-based data acquisition system. The need for further improvements to the prototype optics arrangement was identified. RF heating produced, via thermal conduction, degradation of some of the plastic associated with the fiber optics occurred. The fiber optic plastic sheathing was subsequently removed and air-cooling was provided for the next series of tests. The system was installed for a period of eleven days and performed well during three days of testing. The system operated automatically over extended periods. Different deposition parameter settings were tested. Example results are shown in Figures 15 taken over a 100-minute period. The temperature ranged in between 860 and 880 F (460 to 470 C). As indicated by the data, there was a process change approximately 70 minutes into the run, which resulted in a slight decrease in sheet temperature. In order to assess the possible error associated with the measurement, the deviation of data taken over the course of several minutes was analyzed. This is depicted in Figure 16. It assumes that the deviation in the temperature measurement during this period was entirely due to system error. With that assumption, it is seen in the figure that the measurement varied, in the worst case, over a range of 8 F, thus yielding a standard deviation of ± 5 F. Although, throughout most of the measurement, it was approximately ± 3 F. This is a worst case since it is possible that the temperature actually was changing during the test. This final test also incorporated the custom IO board into the data acquisition system. As stated previously it performs timing, controlling, and signal-conditioning functions. Figures 17 and 18 show additional data in comparison to infrared pyrometers and the zinc pot temperature. The power to the AJAX induction furnaces is also depicted in these two figures. Notice that in Figure 17 the phosphor thermometer shows a decrease in temperature as this power decrease near the end of the run. Figure 19 is a photograph of the installation.

Figure 15. Field Test Results.

8-20-96 Midwest Steel Galvanneal Test

Figure 16. Measurement Error.

Figure 17. Comparison of Results.

Figure 18. Comparison of Additional Results.

Plant Installation

Figure 19. Installation Close-up.

3.0 CONCLUSIONS AND RECOMMENDATIONS

This report describes a new monitoring and control tool for the production of galvanneal steel. It provides for online temperature measurement of the sheet as it emerges from the zinc bath. It is a reliable means to track this critical production parameter.

The project drew upon phosphor thermometry research and experience which began in the early 1980's for the Department of Energy's uranium enrichment enterprise and the extensive Oak Ridge National Laboratory capabilities in instrumentation and controls that have evolved originally from nuclear energy and other programs.

A key factor in the success of this project was the opportunity to perform field-testing on the galvanneal line at National Steel. To move instrumentation from the laboratory to the application requires "real world" testing. The experience of the authors is that test trials and evaluations typically reveal key issues that, early in the project, may be readily accommodated or solved in the instrument design. Future developments for the U. S. steel industry should utilize this same philosophy.

With the experience gained in performing this endeavor, the authors believe that this technology is adaptable to other steel manufacturing applications. For such situations as slab heating, rolling mills, and melts the conditions will be different and slight or extensive modifications to the existing approach may be necessary.

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