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Application of phosphor thermometry to galvanneal processing

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Abstract

A system has been developed for determining temperatures of galvanneal steel during the production process. It is based on an optical method known as phosphor thermometry and it provides for reliable, emissivity-independent measurements. This development is a part of the American Iron and Steel Institute's (AISI) Advanced Process Control Program, a joint endeavor between the AISI and the U. S. Department of Energy. Galvanneal is a corrosion-resistant steel that is widely used for automotive and other applications. Improved thermometry should enable steelmakers to significantly improve product quality as well as to increase the yield, ultimately decreasing costs.

Keywords: fluorescence, fluorescence lifetime(s), temperature measurement, optical method(s), fiberoptics, galvanneal steel.

Introduction

The objective of this project was to develop and demonstrate a prototype system for in-process measurement of galvanneal steel strip temperatures. Reliable temperature measurements will enable more complete galvanneal process characterization and the derivation of a dynamic model for the control of the process. Process variations that are exhibited in surface temperatures of the steel sheet at the galvannealing stage of processing directly affect the quality of the steel and therefore the competitiveness of U. S. Steel industries in a world-wide market. Currently, no accurate in-process measurement of galvanneal steel surface temperature is available which is independent of emissivity. Several parameters will vary during production, such as sheet thickness, sheet speed (which is up to 350 ft/min), and power to the induction furnaces. All of these affect the steel surface temperature and, hence, must be controlled in real time to achieve a high quality end product. The projected benefit of the technology is enhanced product quality, less product variability, and reduced process spoilage.

Background

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 a phosphor decreases exponentially 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 the decay is described by a single exponential 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; however, there are other fluorescence properties that may be exploited to ascertain temperature (eg. 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 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; ie. 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 a surface's emissivity. Because, the emissivity of the molten layer of zinc on the sheet varies rapidly during the process, pyrometry is subject to corresponding uncertainty.

Preliminary Tests and Development

A glove box test was performed to establish the feasibility of this method for measuring galvanneal steel. One purpose was to determine if a sufficient amount of phosphor powder would adhere to the molten surface layer as the sheet emerges from the zinc bath. Another was to determine if the properties of either the phosphor or steel were affected. The test arrangement is shown in Figure 2. As a test strip was retracted from a molten zinc container, phosphor dust was gently puffed onto the surface. This simple demonstration revealed that the powder could be applied to the galvanneal strip and still fluoresce. Subsequent analysis of the fluorescence showed that there was neither a discernible chemical reaction between the phosphor and the strip nor an effect on the physical characteristics of the steel. Shown here in Figure 3 are spectra from a pure phosphor powder sample. in this case YVO_4:Eu, and from this phosphor on the galvanneal specimen. Fluorescence from the latter was weaker than for the pure powder but normalization shows that these spectra are identical in shape. The slightly increased signal near 560 nm for the glove box sample is due to scattered light and is an artifact of the high gain setting. An advantage of the decay time technique is that it is independent of how much phosphor adheres and the overall intensity level.

As part of the development effort, several field tests were conducted to establish the available signal levels, to provide operating experience in the application environment, and to uncover any unforeseen problems. For instance, 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 4. 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 5. The sharp spike at the beginning of the decay curve is due, in this case, to some leakage of laser light (< 1 μs) to the detector. The data acquisition system ignores this part of the decay curve in determining the lifetime of the fluorescence.

System Description

A schematic diagram of the system is shown in Figure 6. A phosphor-deposition device applies the phosphor, under command from a control computer. As seen in the figure, this deposition takes place several feet below where the temperature measurement equipment is located. This allows time for the thin phosphor layer to become equilibrated in temperature with the galvanneal surface. A laser provides, via an optical fiber, illumination of the phosphor. A given phosphor region will be targeted several times by the laser so that a desired number of waveforms are accumulated and averaged to achieve a good statistical sampling. Another optical fiber conveys the fluorescence signal to a remotely located photomultiplier tube detector, which converts this optical signal to its electrical analog. The data analysis system is built around a personal computer using some commercial as well as ORNL-designed hardware and software. The average decay constant of the signal is determined and compared to an on-board calibration equation from which yields the temperature. The most recent temperature is displayed on the monitor. If the system is unable to obtain a stable measurement, no update occurs and the process is repeated.

Different phosphor materials may be used depending on the temperature range of interest, see reference 4. The inset in Figure 6 shows a fit of temperature versus decay time data for one phosphor tested for this project which exhibits moderately high temperature capability. Figure 7 shows some example data taken over a 100-minute period. The temperature ranged 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. The measurements were accurate to ±5 F with a confidence level of 95%.

Conclusions

This project has demonstrated the overall viability of the approach and established that reliable temperature measurements can be made. The AISI is taking steps to commercialize this instrumentation so that a product will eventually be available to the steel industry. To utilize the technology for other applications, such issues as optical access, mechanical fixturing, phosphor adhesion, compatibility, and temperature range should be addressed. With these considerations, the approach should be generally applicable to other steel industry situations such as in re-heat ovens and rolling mills and to other webb processes where temperature is an important parameter.

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ORNL-DWG 97-1687 EFG

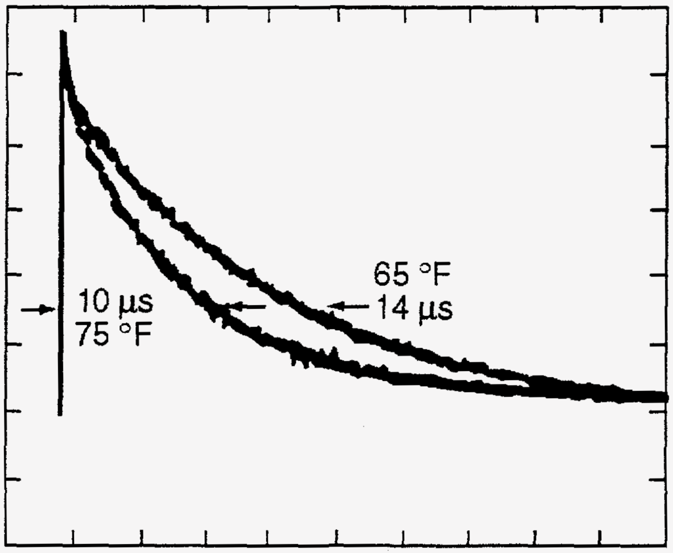

Figure 1. Fluorescence Time Dependence of La_2O_2S:Eu with decay times of 14 and 10 µs at 65 and 75 F, respectively.

ORNL-DWG 97-1688 EFG

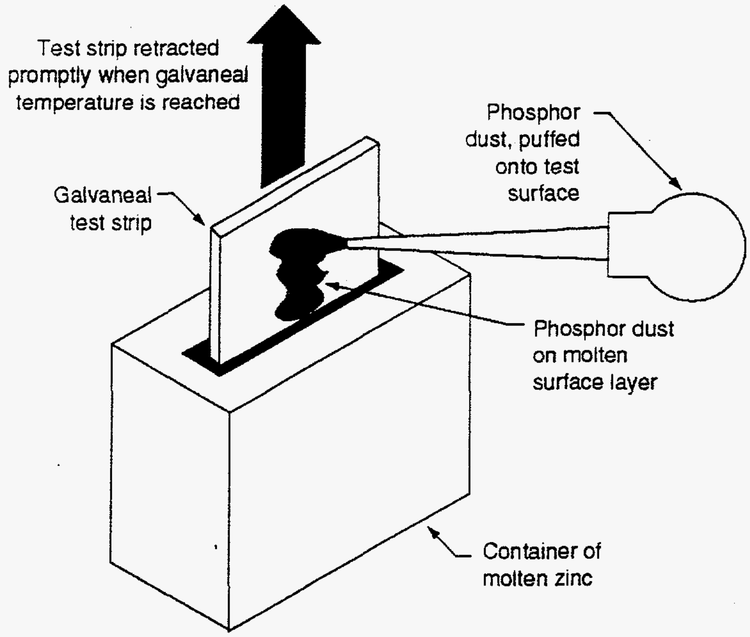

Figure 2. Glove Box Test.

ORNL-DWG 97-1689 EFG

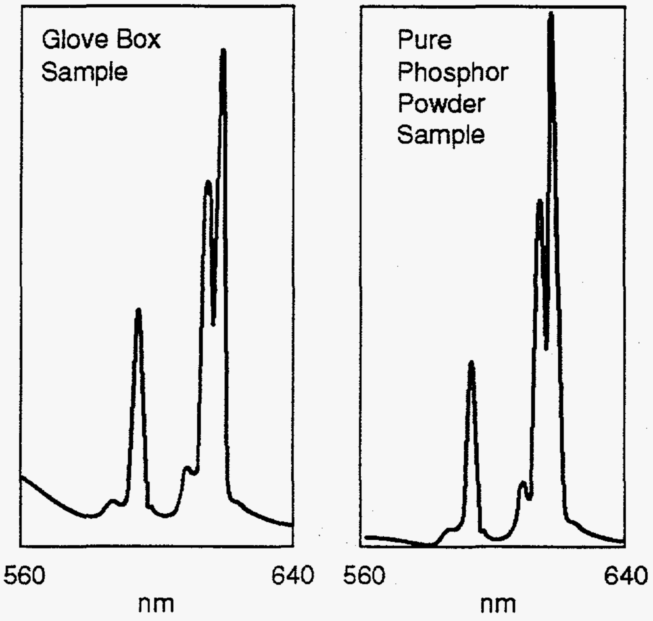

Figure 3. Fluorescence spectra of pure phosphor and phosphor on glavanneal. (Vertical scale: intensity arb. units, Horizontal scale: wavelength in nm.)

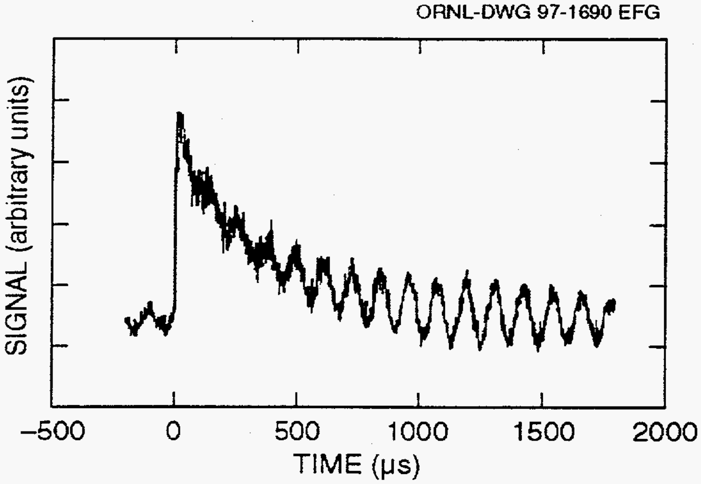

Figure 4. Fluorescence signal with RFI superimposed.

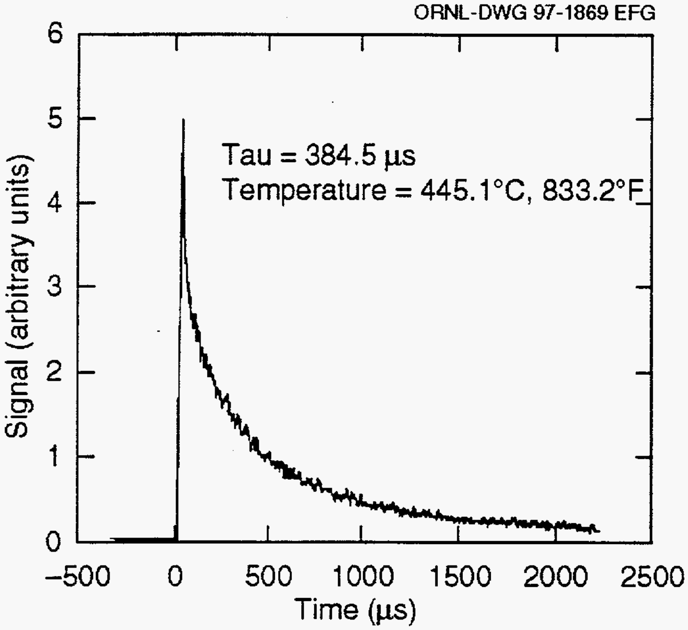

Figure 5.. Fluorescence signal with fiberoptics used.

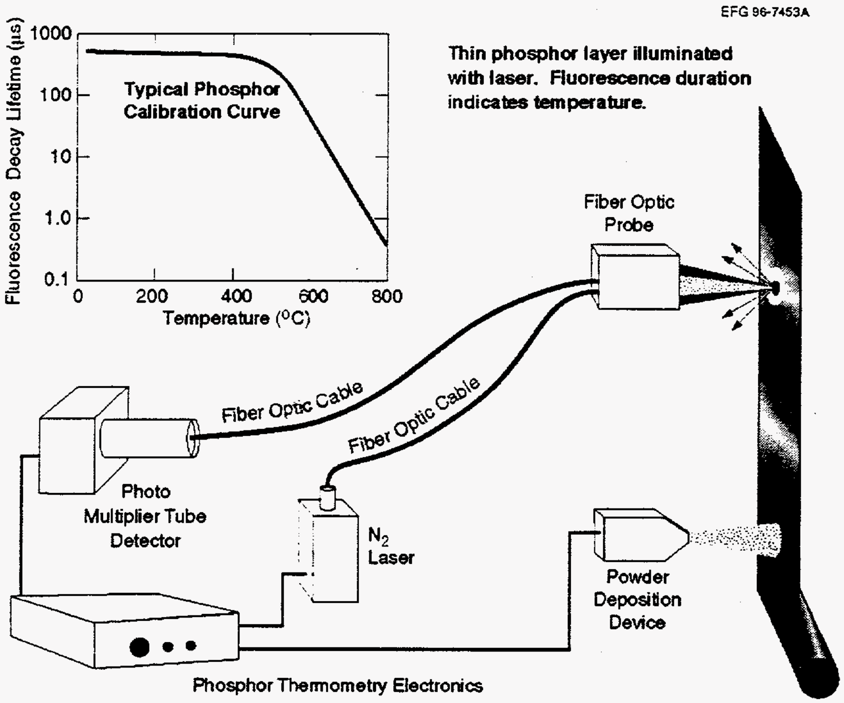

Figure 6. System Schematic.

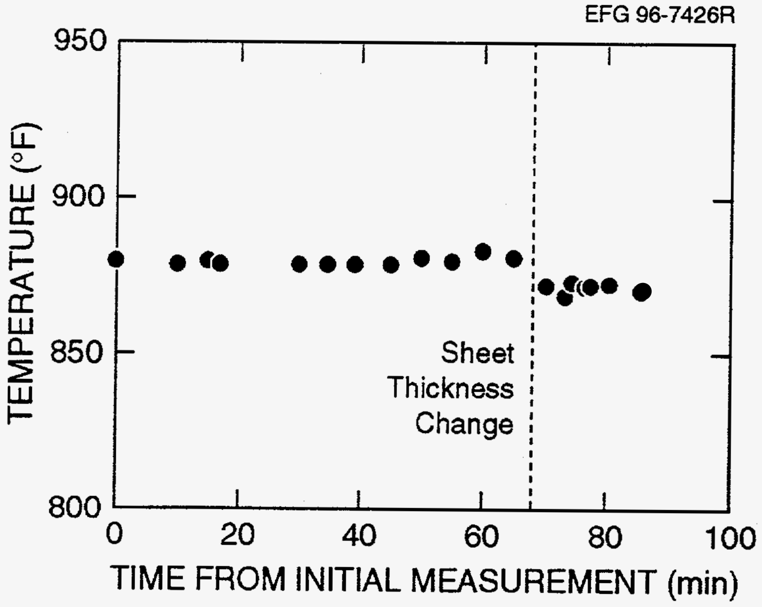

Figure 7. Field Test Results.

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