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Temperature Measurements During the Galvanneal Process

L.K. Zentner[1], D.P. DeWitt[1], and D.A. White[2]

[1]*School of Mechanical Engineering, Purdue University, West Lafayette, Indiana (USA)*

[2]*Inland Steel Research Laboratories, East Chicago, Indiana (USA)*

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ABSTRACT

During the galvanneal process, zinc-coated steel sheet is rapidly heat-treated in order to develop desirable characteristics in the material. The surface changes rapidly from a layer of highly specular liquid zinc with a spectral emissivity of approximately 0.1 to a highly diffuse intermetallic layer with an emissivity as high as 0.8. The variability of the emissivity makes application of traditional non-contact temperature measurement unreliable. This study explored the use of a linear relationship between two spectral emissivities together with Planck's equation to simultaneously determine temperature and spectral emissivities. A laboratory simulation of the galvanneal process was performed in order to obtain spectral radiance and temperature data, from which emissivities were calculated. Results obtained indicate that this dual-wavelength radiation thermometry method can infer temperature to within +/- 50 K. Hence, a simple linear relationship between the emissivities is not adequate for accurate temperature measurement. The results suggest that development of a non-linear equation relating the emissivity values, or an equation including temperature as a parameter, would reduce the temperature errors.

INTRODUCTION

The galvanneal process is an extension of the hot-dip galvanizing process, where cleaned steel strip is coated with a thin layer of zinc, then heat-treated in order to stimulate the growth of an iron-zinc intermetallic layer. In the commercial process, a strip of steel is continuously fed from a payoff reel (coil), through a cleaning section, then into a bath of molten zinc (also referred to as the pot), Figure 1. The strip then passes through coating control knives, which regulate the thickness of the zinc coating. Next, the strip passes through the galvanneal furnace, reaching the

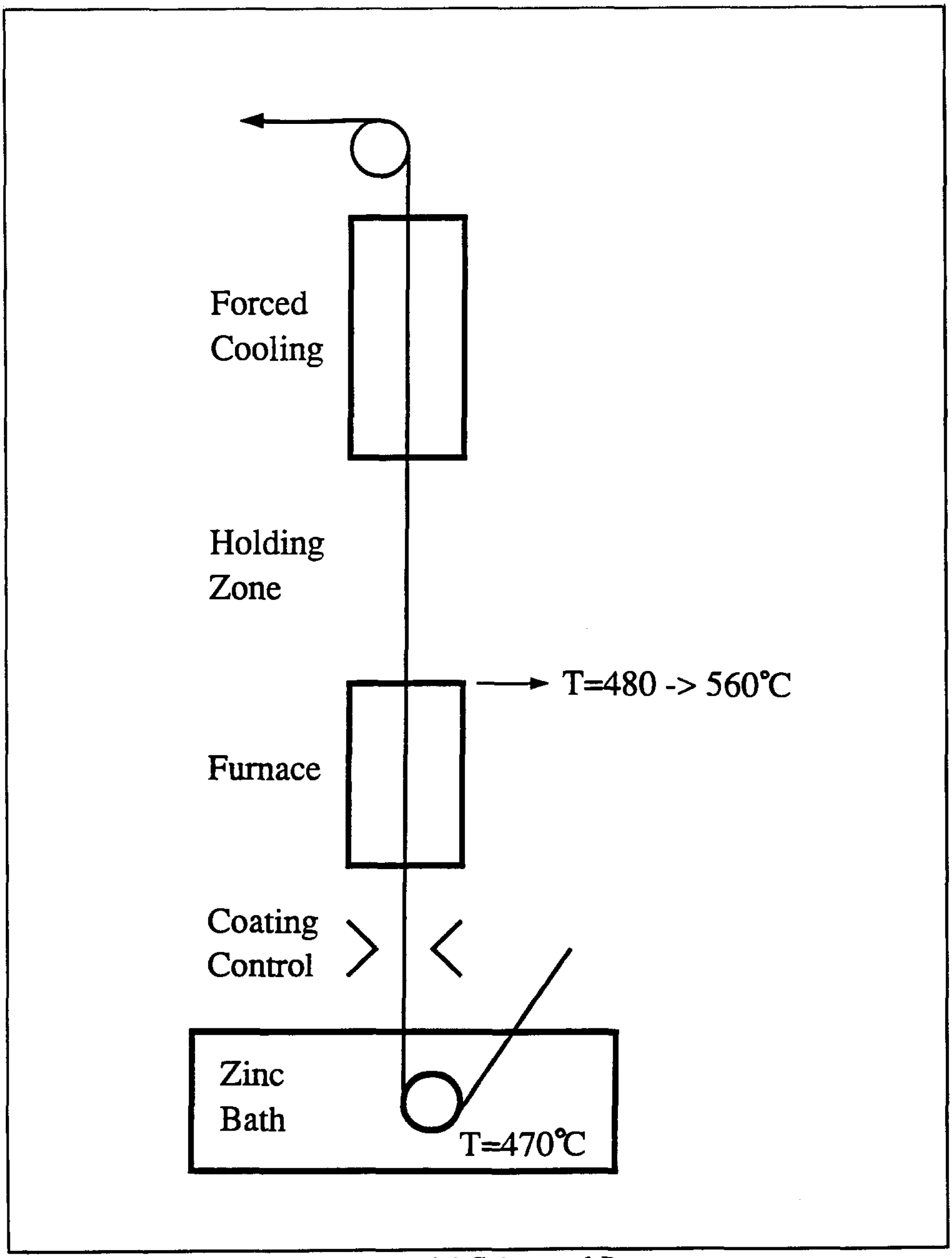

Figure 1: Schematic of the Commercial Galvanneal Process

desired galvanneal temperature by the time it exits the furnace. As the strip passes through the holding zone (free cooling section), the temperature drops only slightly, and diffusion of the iron into the zinc coating layer occurs. The extent of the iron-zinc interaction is dependent upon the magnitude of the galvanneal temperature as well as the length of time the strip spends passing through the free cooling section. The forced cooling section halts the formation of the intermetallic layer by rapidly cooling the strip, and when the sheet is completely cooled, it is coiled. Because the transformation from a layer of pure zinc on steel to a complex intermetallic layer occurs quickly and is temperature dependent, surface temperature measurement becomes an important task.

During the galvanneal process, the emissivity of the surface changes from approximately 0.1 (highly specular) for pure liquid zinc to as high as 0.8 (diffuse) for a fully alloyed intermetallic layer. Non-contact temperature measurements taken at a single spectral band (spectral radiometry) require a constant, known value of emissivity for accurate measurements. Use of a single wavelength method is not practical for this varying emissivity application. Dual-wavelength methods provide spectral radiance data in two distinct spectral bands. These data, together with a functional relationship between the two spectral emissivities, can be used with Planck's equation to determine the temperature of the target [DeWitt and Nutter, 1988; Tsai, 1990]. Utilizing a functional representation of the behavior of the spectral emissivities in order to infer a temperature is referred to as emissivity compensation.

Benefits of better temperature measurement include easier, more exact process control, as well as the ability to produce a more consistent final product. The properly processed galvannealed product has the advantages of good paint adherence and corrosion resistance. A non-contact method is preferred for this application for several reasons. First, rapid line movement and strip vibration preclude the use of contact methods. Further, undesirable material scarring would also be a serious quality problem with contact methods. Finally, non-contact methods provide the potential for determining process parameters other than surface temperature, such as emissivity. Dual-wavelength radiometry is an obvious choice for this application.

The objective of this study was to develop an improved method of temperature measurement for the galvanneal process, using dual-wavelength radiation thermometry. The desired product of this research is an algorithm which can infer strip temperature from the spectral radiance values measured by a dual-wavelength radiometer. The algorithm must be robust enough to perform well for a diverse set of process conditions.

The basis of this study is a set of experiments performed in the laboratory on samples submitted to typical temperature-time profiles. The laboratory studies provided an opportunity to simulate the actual commercial process conditions in a controlled environment. A suite of samples were processed in the laboratory with varying temperature-time profiles. In situ measurements of spectral radiance at two wavelengths, as well as sample temperature were taken. Emissivities were calculated and used to develop an algorithm which, given two spectral radiance values, can be used to solve for unknown values of temperature and emissivity. The output from the algorithm was used to determine how well the inferred temperature compared to the known temperature for the simulated process conditions. Results were compared to the spectral and ratio methods of emissivity compensation.

EXPERIMENTAL PROCEDURE - PROCESS SIMULATION

The laboratory simulations of the galvanneal process were performed using a Gleeble 1500 (Duffers Scientific), an apparatus which can rapidly heat a sample using alternating current, and at the same time, control the temperature-time profile and record the actual temperature of the sample. Temperature control was achieved using a type-K thermocouple spot-welded to the back side of each sample. Previous studies [Smith, et al., 1989] have shown that the Gleeble is adequate for simulating the commercial galvanneal process. A set of 19.05 cm by 4.45 cm zinc-coated steel samples was used for the experiments. Seven samples were processed for each of nine different temperature-time profiles, yielding a total of sixty-three samples. The different profiles represented combinations of three different galvanneal temperatures and three different line speeds or soak times. Galvanneal temperatures ranged from 480 °C to 560 °C. Simulated line speeds varied between 60 m/min and 100 m/min. These conditions were selected in order to yield results representative of the scatter that would be seen in a real mill application. A custom dual-wavelength radiation thermometer (DWRT, Williamson Corp.) was mounted vertically, with its faceplate approximately 45 cm from the target. A heat transfer analysis showed that the center of the sample was isothermal up to a diameter of approximately 2.5 cm. The infrared field of view of the instrument was approximately 1.27 cm in diameter. The DWRT sampled data at spectral bands of 2.18 μm (0.3 μm wide) and 2.4 μm (0.2 μm wide). A microcomputer-based data acquisition system sampled the data from the thermocouple and the DWRT at a rate of approximately 7 Hz. The DWRT was calibrated on each day of experiments using a laboratory blackbody (Williamson Corp., Model # 45).

Each sample was first heated quickly to 470 °C in order to melt the zinc. Next, the sample was ramped up to the galvanneal temperature at a rate corresponding to the line speed being simulated. The sample was then held at the galvanneal temperature for a time period corresponding to the pass through the holding zone. Finally, the sample was rapidly cooled using a water quench to preserve the microstructure of the sample for future studies. Figure 2 shows an example of the heating curve for a sample.

DATA ANALYSIS

The laboratory measurements yielded the sample temperature, T, as well as the sample radiances, L_1 and L_2 at the two separate wavelengths, λ_1 and λ_2. By applying Planck's equation for a blackbody at each wavelength and temperature

$$L_{\lambda,b} = \frac{c_1}{\lambda^5[\exp(c_2/\lambda T)-1]} \tag{1}$$

the blackbody spectral radiances at each wavelength were obtained. Then, by definition, the emissivity was obtained from

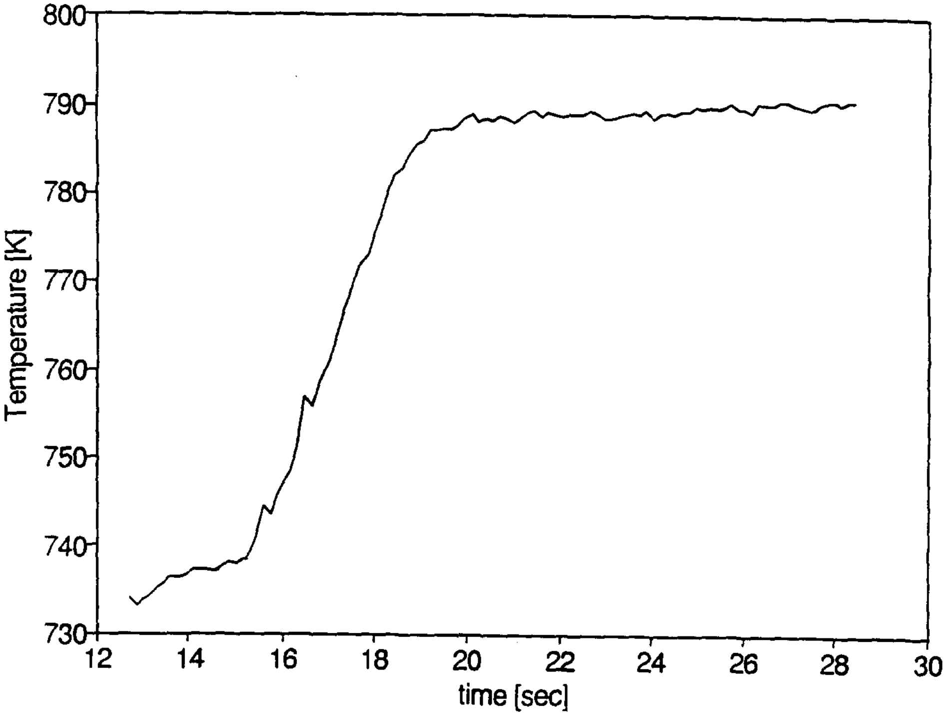

Figure 2: Typical Temperature-Time Profile Representing the Galvanneal Process

$$e_\lambda = L_\lambda / L_{\lambda,b}. \tag{2}$$

Based on the behavior of the spectral emissivity data, Figure 3, a linear relationship seemed appropriate for the first approach to this problem. A linear regression analysis was performed on the entire set of emissivity data in order to obtain a relationship between the two emissivities of the form

$$e_1 = ae_2 + b. \tag{3}$$

This equation will be referred to as the linear compensation equation. Although the coefficients vary slightly for each process condition, it was necessary to develop an equation that fit all of the data in order to obtain a more robust algorithm. Using process specific coefficients would yield improved results for that particular process, but would adversely affect the results should the process conditions change.

Once the reciprocity relationship is known, it can be used together with

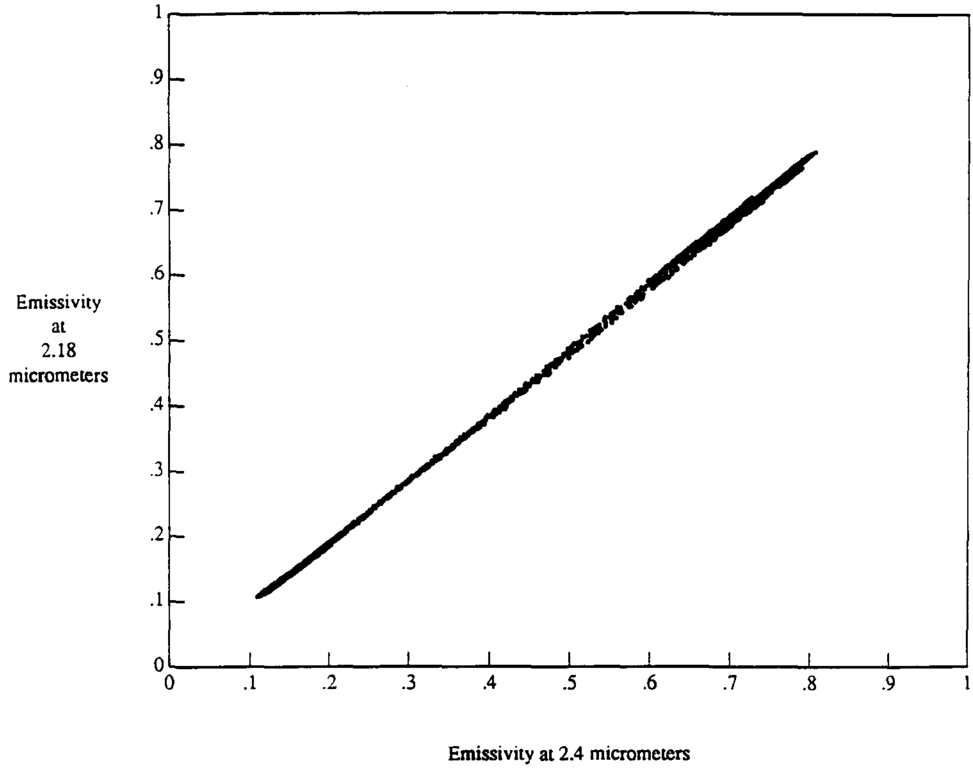

Figure 3: Relationship Between Spectral Emissivities

Planck's equation at each wavelength

$$L_1 = \epsilon_1 \frac{c_1}{\lambda_1^5[\exp(c_2/\lambda_1 T) - 1]} \tag{4}$$

$$L_2 = \epsilon_2 \frac{c_1}{\lambda_2^5[\exp(c_2/\lambda_2 T) - 1]} \tag{5}$$

$$\epsilon_1 = a\epsilon_2 + b \tag{6}$$

to complete a system of three equations and three unknowns, the unknowns being the actual sample temperature, T, and the two emissivities, ε_1 and ε_2. The nature of the system of non-linear equations requires that they be solved iteratively, rather than explicitly. A computer program was written using Newton's method to solve the system for each set of spectral radiance values. The program begins with initial guesses for temperature and the two emissivities. Once a solution is reached for a given data point, the values of temperature and emissivity obtained for that point are used as the initial guess for the next data point. This approach works well for reducing the number of iterations required to solve the system of equations as long as the spectral radiance values do not experience large changes from one data point to the next. Generally, this is true of the strip in the mill, except in cases where there is a malfunction on the line, such as the galvanneal furnace breaking down, or at the beginning of a new coil of strip. Nearly 10,000 data points were processed. The results obtained from the computer program were then compared to the measured emissivities and temperatures and errors were calculated. Figure 4 shows the behavior of the temperature errors for all data points. The difference between the measured and calculated temperatures is plotted for the range of measured emissivity values. Similar behavior was exhibited by the errors in emissivity produced by the program.

DISCUSSION

Maximum errors of +/- 50 K occur predominantly at low emissivities, as seen in Figure 4. At high emissivities, negative errors up to -50 K are obtained. There is a definite pattern to the error plots for various process conditions. Errors begin more or less positive, with a scatter of negative values, at low emissivities, then drop off to large negative values at higher emissivities. For a given line speed (time in holding zone), the slope of the error curve increases with increasing galvanneal temperatures. The magnitude of the error at values of low emissivity also increases with increasing galvanneal temperature. Figure 5 illustrates the small slope exhibited by the error curve for the low galvanneal temperature. Figure 6 shows an increase in the slope of the error curve for the mid-range value of galvanneal temperature. Finally, Figure 7 illustrates the largest slope for the case of high galvanneal temperature. This behavior suggests that temperature could be introduced as a variable in the compensation equation. There seems to be little effect due to different line speeds on temperature errors, except that more points are clustered at low emissivities for fast line speeds, due to the low level of alloying that occurs for a short time in the holding zone.

Comparisons were also made to more simple emissivity relationships, such as the spectral and ratio methods. The spectral method assumes a constant, known emissivity, so spectral radiance for only one wavelength is needed. Using an average emissivity obtained from the laboratory data yielded temperature errors as large as 140 K. Obviously, this approach is not the method of choice.

The ratio method assumes a known, constant ratio of the spectral emissivities. This ratio was obtained by regression of the laboratory data. By taking the ratio of Planck's equation at each wavelength

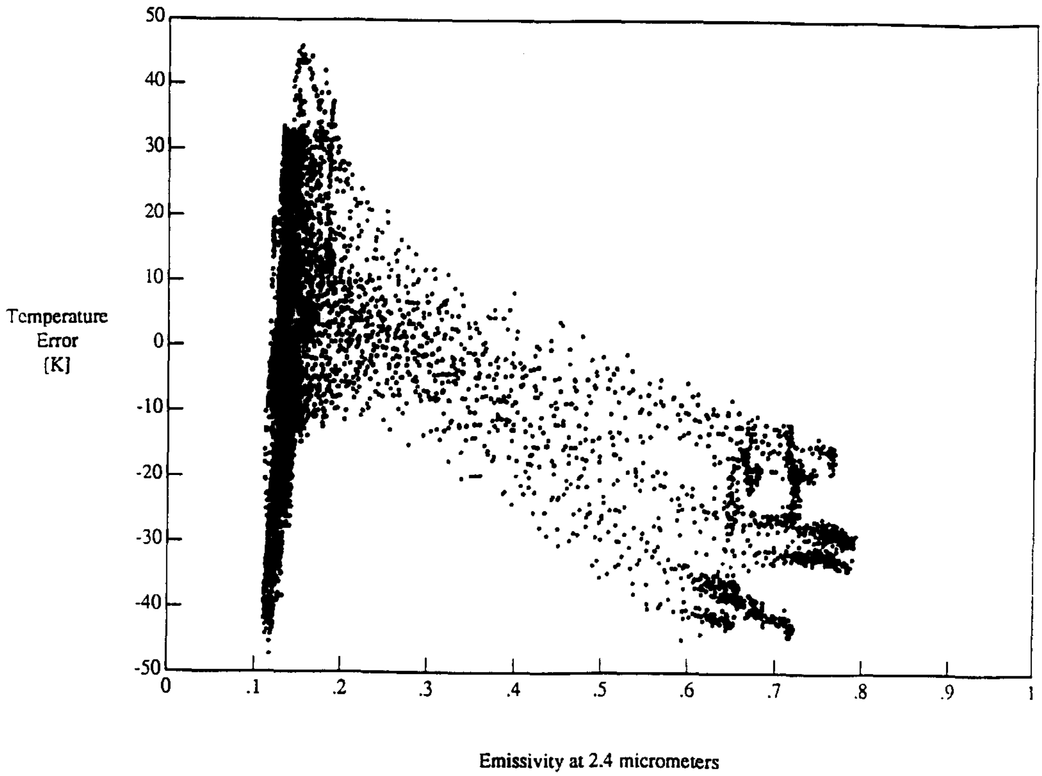

Figure 4: Temperature Errors Using Linear Compensation Relationship

$$\frac{L_1}{L_2} = \frac{\epsilon_1}{\epsilon_2} \frac{\lambda_2^5}{\lambda_1^5} \frac{[\exp(c_2/\lambda_2 T) - 1]}{[\exp(c_2/\lambda_1 T) - 1]} \tag{7}$$

and inserting the ratio of the emissivities, the temperature can be obtained as long as the spectral radiance values are known. This method yields error plots that are very similar to those obtained using the linear compensation equation, except that they are offset in the positive direction by approximately 20 degrees. Overall, the magnitude of the errors from the ratio method are generally larger than those obtained using a linear compensation function. Even in cases where the ratio method errors are slightly smaller, the functional compensation method offers the advantage of improved results through the use of a more sophisticated emissivity relationship. Further research will attempt to define more appropriate compensation relationships in order to further reduce temperature errors.

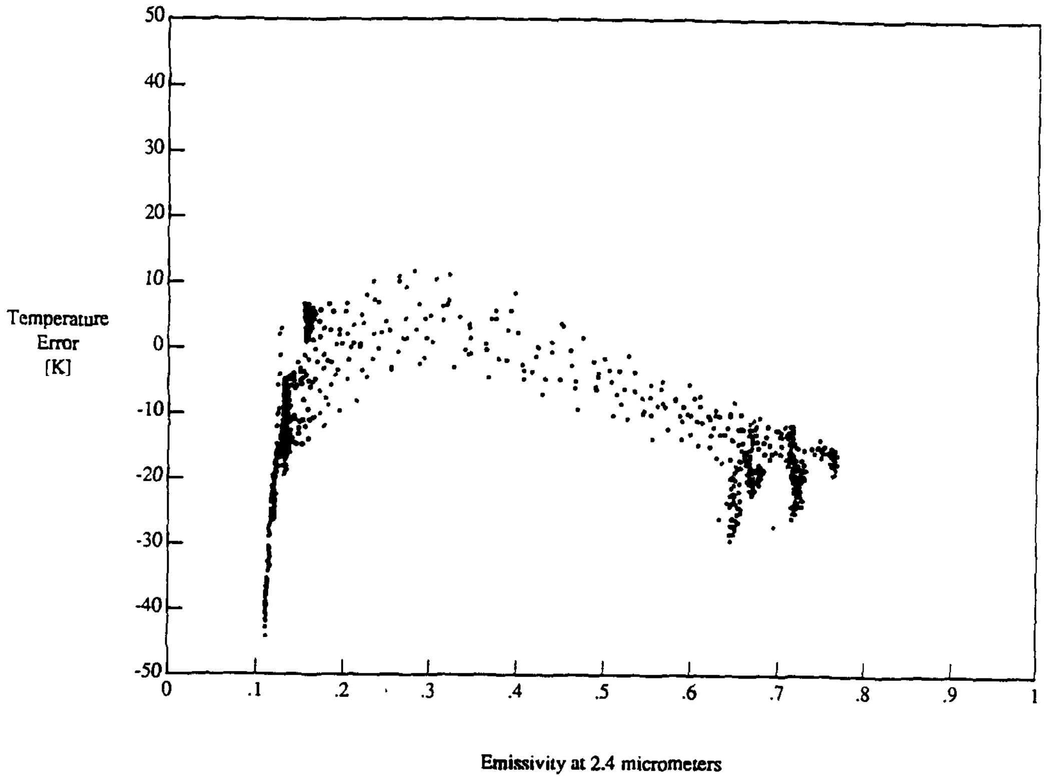

Figure 5: Temperature Errors at Low Galvanneal Temperature, Low Line Speed

CONCLUSIONS AND RECOMMENDATIONS

The trends in the results from the algorithm suggest that there is some form of temperature dependence in the errors. The next step in the research will be to perform a multivariate regression on the emissivities and temperature in order to develop a more complex compensation relationship. In addition, other functional representations of the parameters will be explored. Although Figure 3 would seem to indicate that a linear relationship adequately represents the emissivity behavior, it is clear that dual-wavelength radiation thermometry is very sensitive to the form of the compensation relationship. The linear representation is simply a starting point in the analysis, and indicates that other more complex relationships must be developed. It may also be possible to develop different functional relationships for several emissivity intervals, in order to reduce the errors in each portion of the process. However, discontinuities which occur where the intervals overlap may cause some difficulties in utilizing Newton's method to solve the system of non-linear equations.

In any method for solving a system of non-linear equations, an initial guess is

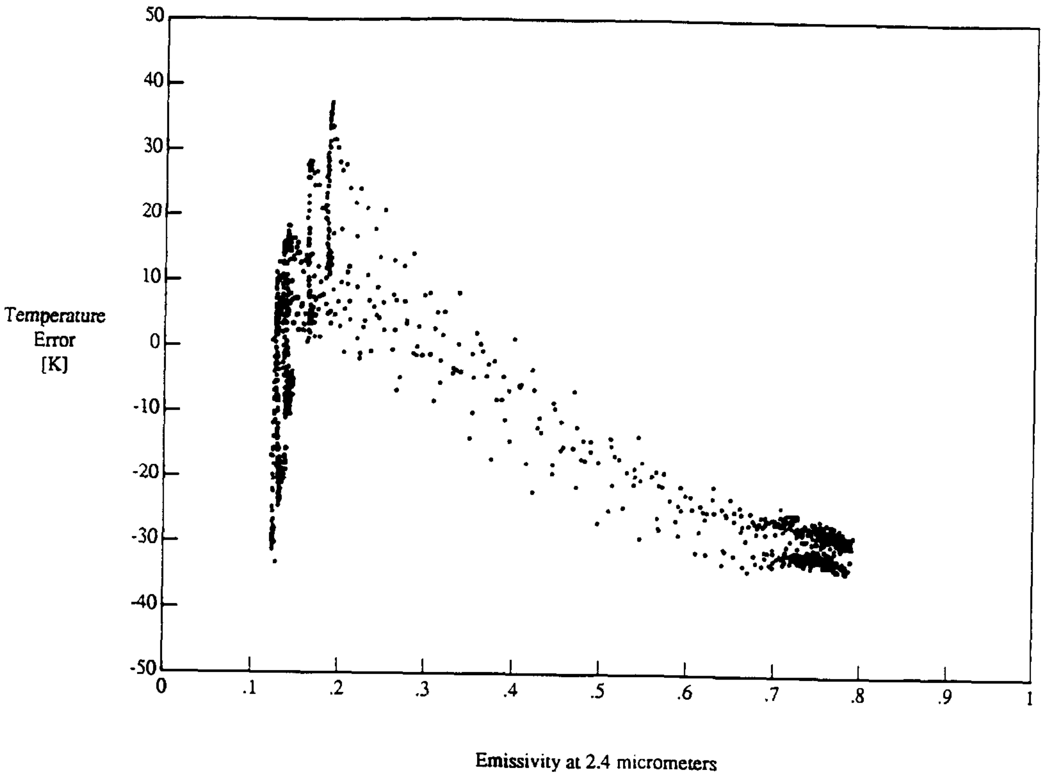

Figure 6: Temperature Errors at Medium Galvanneal Temperature, Low Line Speed

required. It is possible that the solution may be sensitive to the value of the initial guess. Thus, another future task will involve performing a sensitivity analysis on the values of the initial guesses, resulting in some sort of "smart module" in the algorithm, which can select an appropriate value of the initial guess based on the magnitude of the spectral radiances sensed by the instrument. This module would also account for on-line malfunctions and changes from one material to the next. Preliminary evaluation suggests that errors related to initial guess values exist, but are not large.

Although the algorithm presently under study currently yields larger than desirable errors for some emissivity values, the potential is there for much better accuracy with increased refinement. This analysis has completed the first step in the research, and the results have pointed the way to further refinements which may lead to reduced temperature errors. It is clear that a great deal of flexibility is available through the use of the functional compensation method, and by utilizing this method, accurate temperature measurement should soon become possible for this particular application.

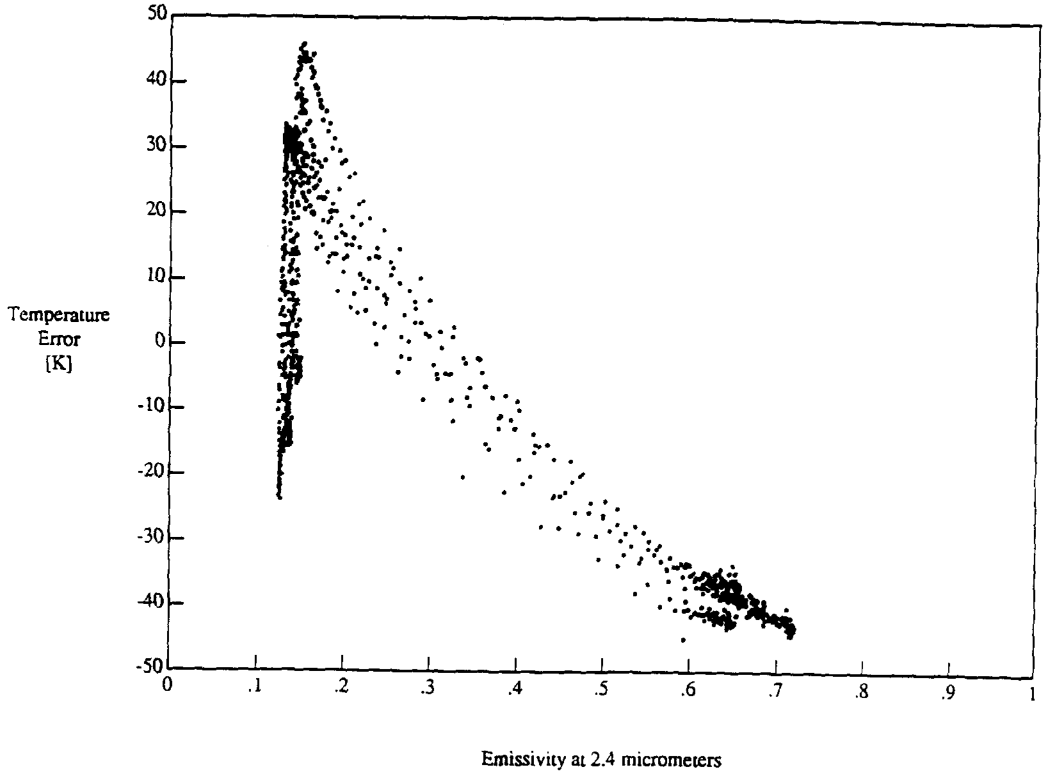

Figure 7: Temperature Errors at High Galvanneal Temperature, Low Line Speed

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