Impact of evolving spectral emissivity on pyrometry during intercritical annealing

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Abstract

Wavelength-dependent variations in the spectral emissivity of advanced high strength steels (AHSS) leads to errors in pyrometry measurements during intercritical annealing, which in turn affect the mechanical properties of the steel. This study presents in-situ spectral emissivity measurements for a dual-phase steel (DP980) heated in an annealing simulator with a reducing atmosphere. The variation of the spectral emissivity with wavelength, temperature, and time is measured simultaneously using a near-infrared spectrometer and a multi-wavelength pyrometer, providing insights into how the evolving surface state affects the spectral emissivity and the pyrometrically-inferred measurements. Comparing the spectral emissivity and temperature estimates obtained by ratio and multi-wavelength pyrometry methods indicates that multi-wavelength pyrometry provides more accurate emissivity and temperature estimates for annealing AHSS.
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1. Introduction

Galvanized advanced high strength steels (AHSS) are used in the automotive industry to improve fuel efficiency and reduce pollutant emissions without compromising passenger safety. An integral part of the manufacturing process is the heat treatment furnace, which requires precise thermal control during the intercritical annealing phase to obtain the desired mechanical properties in the steel. Substandard mechanical properties are often attributed to temperature excursions during intercritical annealing of the AHSS caused by errors in the pyrometrically-inferred temperatures used for furnace control. The errors in the pyrometer readings originate from the evolving surface state of the steel strip, in terms of roughness and oxidation, during thermal processing, which lead to wavelength-dependent variations in spectral emissivity [1-3].

Many experiments (e.g. [4-9]) have investigated how the spectral emissivity of steel and aluminum sheet vary during heating. Wen [4] examined the effect of wavelength, temperature, alloy composition, and heating time on the spectral emissivity of several steel samples while simultaneously evaluating the performance of six emissivity models used in multi-wavelength pyrometry. Shi et al. [5] investigated how coating evolution and different heating atmospheres (argon and air) affected the spectral emissivity of Al-Si coated 22MnB5 steel. González-Fernández et al. [6] analyzed the influence of thermal cycling and surface roughness on the spectral emissivity of the Ti–6Al–4V alloy between 500 and 1150 K in the mid-infrared spectrum (2.5μm – 22μm). Comparatively few studies have focused on the relationship between the evolving surface state and the spectral emissivity of uncoated AHSS. Ham et al. [7, 8] studied the correlation between the spectral emissivity of cold-rolled TRIP steel annealed within reducing atmospheres of various dew points and the resulting ex-situ surface roughness and oxide type. They found that the RMS roughness measured with an optical profilometer is not directly related to the spectral emissivity, which was confirmed by Somveille et al. [9]. Following the work of Ham et al. [8], Lin and Daun [10] developed a model for the spectral emissivity of DP980 steels based on Kirchhoff-Helmholtz theory.

This study explores the connection between the evolving surface state and the spectral emissivity, and thus the pyrometrically-inferred temperature for AHSS coupons heated within a measurement chamber, similar to the one used by Ham et al. [7, 8]. Coupons of DP980 alloy are heated within a controlled reducing atmosphere of 95% N₂/5% H₂ and a dew point of −40°C. Spectral irradiance is measured simultaneously with a near-infrared spectrometer (0.9μm – 2.5μm) and a multi-channel pyrometer (1.6μm, 2.1μm, and 2.4μm). The visible change in the appearance of the steel surface is related to the observed spectral emissivity variation. The performance of ratio and multi-wavelength pyrometry methods for estimating the surface temperature of AHSS is also examined.

2. Principles of Pyrometry

Single-, dual-, and multi-wavelength pyrometry are mainstay techniques for measuring the temperature of steel strips during AHSS production. The signal generated by the pyrometer at a given detection wavelength is found by integrating the spectral intensity over the spectral width Δλ of a bandpass filter centered at the detection wavelength

\[ L_{λ_{d}} = ΔΩ_{d}·A_{d}·\int_{Δλ} η_{λ} (λ) · ε_{λ} (λ, T, \theta) · I_{λ,θ} (λ, T) dλ \] (1)
where \( T \) is the surface temperature, \( A_d \) and \( \Delta \Omega_d \) are the detector area and detection solid angle, respectively, \( \eta \) is the optoelectronic efficiency of the pyrometer, \( I_{\lambda b} \) is the blackbody intensity, \( \varepsilon_{\lambda}(\lambda, T, \theta) \) is the spectral emissivity, and \( \theta \) is the angle formed between the optical axis of the pyrometer and the surface normal of the steel strip. In practice, the spectral width of the bandpass filter is sufficiently narrow such that the signal can be modeled by

\[
L = \Delta \Omega_d A_d \cdot \eta \cdot (\lambda_d) \cdot \varepsilon_{\lambda}(\lambda_d, T, \theta) \cdot I_{\lambda b}(\lambda_d, T) \Delta \lambda
\]

where \( \lambda_d \) is the center wavelength. At sufficiently small values of \( \lambda T \), the blackbody spectral intensity is given by

\[
I_{\lambda b}(\lambda, T) = \frac{2hc_0^2}{\lambda^5 \left[ \exp \left( \frac{C_2}{\lambda T} \right) - 1 \right]} \approx \frac{2hc_0^2}{\lambda^5 \left[ \exp \left( \frac{C_2}{\lambda T} \right) \right]}
\]

where \( C_2 = \frac{hc_0}{k_B} = 1.439 \times 10^4 \text{ µm} \cdot \text{K} \), \( h \) and \( k_B \) are the Planck and Boltzmann constants, respectively, and \( c_0 \) is the speed of light in vacuum. Substituting Eq. (3) into Eq. (2) results in

\[
L = \Delta \Omega_d A_d \cdot \eta \cdot (\lambda_d) \cdot \varepsilon_{\lambda}(\lambda_d, T, \theta) \cdot \Delta \lambda \cdot \frac{2hc_0^2}{\lambda_d^5 \left[ \exp \left( \frac{C_2}{\lambda_d T} \right) \right]} = \frac{C_{\lambda d} \varepsilon_{\lambda}(\lambda_d, T, \theta)}{\lambda_d^5 \left[ \exp \left( \frac{C_2}{\lambda_d T} \right) \right]}
\]

where \( C_{\lambda d} \) is treated as a calibration constant. The scheme used to relate \( \lambda T \) from \( L \) depends on the number of wavelengths at which the spectral irradiance is measured. The most common approaches are single-wavelength (SW), dual-wavelength (DW), and multi-wavelength (MW).

### 2.1. Single-wavelength Pyrometry

Single-wavelength (SW) pyrometry utilizes the spectral irradiance measurement at one wavelength to infer the temperature of the surface. It is most suitable for stable materials [11] as it assumes that the target surface has a constant and known spectral emissivity. The SW pyrometry temperature is obtained by inverting Eq. (4)

\[
T = \frac{C_2}{\lambda d \ln \frac{\varepsilon_{\lambda} C_{\lambda d}}{\lambda_d^5 L}}
\]

Correctly inferring the temperature of AHSS using SW pyrometry is very difficult because \( \varepsilon_{\lambda} \) is known to vary with temperature, surface roughness, and oxide formation as the steel is being annealed. For this reason, this approach can only be applied in “wedge” type configurations, in which the pyrometer is aimed precisely at the center of the notch formed between the steel strip and the roll, where the spectral emissivity is close to unity due to the blackbody cavity effect [12]. Any misalignment in aiming the field of view of the pyrometer greatly influences the inferred temperature. In addition to the geometry and alignment, the SW temperature reading is highly sensitive to any temperature difference between the strip and the roll.

### 2.2. Dual-wavelength Pyrometry

Dual-wavelength pyrometry utilizes the spectral irradiance measured at two distinct wavelengths, \( \lambda_{d1} \) and \( \lambda_{d2} \) to estimate surface temperature. Although dual-wavelength pyrometry can be used in applications with unknown spectral emissivity, it still requires a priori knowledge of the relationship between the spectral emissivity at the two wavelengths. The spectral emissivity at one
wavelength is typically expressed as a reciprocity function of the other, i.e. \( \varepsilon_{\lambda_{dl}} = f(\varepsilon_{\lambda_{d2}}) \) \[11, 14\]. Dual-wavelength pyrometry is more robust to errors caused by atmospheric absorption and partially-filled fields-of-view as the ratio of the measured spectral irradiances cancels out these effects.

The most common subset of DW pyrometry is the *ratio (two-color) pyrometry* in which

\[
T = \frac{C_2}{\ln \left[ \frac{\varepsilon_{\lambda_{d2}} \left( \frac{\lambda_{d2}}{\lambda_{dl}} \right)^5 L_1}{\varepsilon_{\lambda_{dl}} \left( \frac{\lambda_{dl}}{\lambda_{d2}} \right)^5 L_2} \right]}
\]

To achieve an accurate temperature estimate, the ratio of the emissivity values, commonly known as e-slope, has to be a known constant independent of temperature and surface conditions, i.e.

\[
e\text{-slope} = \frac{\varepsilon_{\lambda_{dr}}}{\varepsilon_{\lambda_{dl}}} = \text{constant} \tag{7}
\]

For surfaces that can be approximated as gray, \( \varepsilon_{\lambda r} \) is unity. If the emissivity assumption is valid, the ratio temperature estimate becomes more resilient to measurement error as the detection wavelengths move further apart \[13\]. On the other hand, if \( \varepsilon_{\lambda r} \) is not independent of the evolving surface state, the use of wavelengths that are spectrally far apart increases the error.

### 2.3. Multi-wavelength Pyrometry

Multi-wavelength or multispectral pyrometry is usually taken to mean systems that infer the surface temperature from the spectral irradiance measured at three or more discrete wavelengths along with an emissivity compensation algorithm \[15\]. Emissivity compensation algorithms for MW pyrometry are usually polynomial functions derived by empirical or theoretical analysis to model how the spectral emissivity varies with the underlying parameters such as wavelength and/or temperature \[4, 14-16\].

The emissivity compensation models can be solved either by exact or least-square methods \[4, 15\]. To solve for the temperature from \( p \) irradiance measurements by the exact method, the emissivity model should have \( p-1 \) unknown coefficients, while the least square method requires an emissivity model with \( p-2 \) unknown coefficients \[4\], i.e. to infer the surface temperature for a three-wavelength model, the maximum number of unknown coefficients in the emissivity polynomial should be two for the exact method and one for the least square method. While the exact method allows the use of more polynomial coefficients to capture the complex emissivity relationship given a limited number of detection wavelengths, previous investigations into solving emissivity compensation models by exact method shows that this approach tends to result in large errors and overfitting for pyrometers with more than three detecting wavelengths \[16\]. Using the least-square method, on the other hand, will reduce the large errors as it finds the optimum temperature and coefficients values that minimizes the residuals. Multi-wavelength pyrometry not only captures the complex spectral emissivity relationships but also allows for the statistical reduction of temperature errors caused by measurement noise \[15\].

### 3. Experimental Apparatus and Measurement Procedure

#### 3.1. Sample Preparation

The 152.4 mm × 25.4 mm × 1.5 mm coupons were cut from a coil of cold-rolled DP980. The steel’s elemental composition conforms to ASTM A1079-17 \[17\], as detailed in Table 1. Although the
exact composition of the coupon used in this experiment is proprietary, the Mn/Si mass ratio measured by spark atomic emission spectrometry is 25.7. Figure 1 shows the near-normal directional-hemispherical spectral emissivity of the as-received coupons measured with a Bruker Invenio-R FTIR spectrometer. All samples are cleaned with ethanol to remove oil and surface contaminants before annealing.

Table 1. Nominal chemical composition of DP980 [17].

<table>
<thead>
<tr>
<th>Constituents</th>
<th>C</th>
<th>P</th>
<th>S</th>
<th>Mn+Al+Si</th>
<th>Cu</th>
<th>Ni</th>
<th>Cr+Mo</th>
<th>V+Nb+Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>%mass max</td>
<td>0.23</td>
<td>0.08</td>
<td>0.015</td>
<td>6.00</td>
<td>0.20</td>
<td>0.50</td>
<td>1.40</td>
<td>0.35</td>
</tr>
</tbody>
</table>

![Figure 1](image.png)

Figure 1. Plot of $\varepsilon_\lambda$ vs $\lambda$ for as-received DP980 at room temperature.

3.2. Experimental Apparatus

The AHSS coupons are heated in the chamber shown in Figure 2. Each coupon is mounted between two copper electrodes, which are connected to a programmable DC power supply (TDK-Lambda, 8V, 600A). The coupon temperature is controlled with feedback from a K-type thermocouple spot-welded to the back of the sample.

Before the coupon is heated, the thermal processing chamber is continuously purged with 95% N$_2$/5% H$_2$ at a rate of 8 standard liters per minute for at least 20 minutes. A portion of the dry gas mixture is diverted through a tank of deionized water using a mass flow controller (MFC) and then mixed downstream with the dry flow. The dew point of the mixture is measured using a hygrometer (Michell EA2-TX-100-HD), which provides feedback to the MFC. All tests described in this paper were carried out at a dew point of -40°C.

The chamber is outfitted with a Williamson PRO MWX-ST-17 multi-wavelength pyrometer and an OceanOptics NIRQuest512 spectrometer. The pyrometer is equipped with a filter wheel that accommodates bandpass filters centered on wavelengths 1.6μm (1.505μm–1.790μm), 2.1μm (2.025μm–2.23μm), and 2.4μm (2.250μm–2.45μm). The pyrometer is aimed through a 5.08 cm (2”) diameter calcium fluoride (CaF$_2$) window. The spectrometer is connected by optical fiber to a hard-mounted collimating lens that views the coupon at an oblique angle (25°). The spectrometer is sensitive over 0.9μm – 2.5μm; due to low signal-to-noise ratio at the shorter wavelengths, only
measurements over 1.2\(\mu\)m – 2.5\(\mu\)m are reported here. An absolute intensity calibration was carried out on the spectrometer using a blackbody source (Infrared Systems IR-563/301). The pyrometer and spectrometer measurement spot sizes are coincident on the center of the AHSS coupon with a diameter of approximately 2.5 cm. Measurements on a black-painted coupon heated to 850\(^\circ\)C using a FLIR T400 infrared camera suggest that the maximum temperature variation within the measurement spot is 10 K.

Figure 2. (a) Schematic diagram of the annealing simulator apparatus; (b) The annealing simulator, showing the pyrometer and spectrometer optic, and (inset) a heated coupon.

The DP980 coupon is heated to 800\(^\circ\)C according to a linear ramp rate over 60s (13.33\(^\circ\)C/s), soaked at 800\(^\circ\)C for 30s, and then quenched with the process gas. In-situ measurements are conducted only during the sample heating process, so the quench rate is uncontrolled. The spectrometer collects spectra every 0.25s during the sample heating schedule. The pyrometer data acquisition time interval is set to 0.1s for these experiments. The spectrometer data is further smoothed with a first-order, three-frame Savitzky-Golay filter.

4. Results and Discussion

The actual temperature reported by the thermocouple attached to the steel coupon is shown in Figure 3. A straw-colored oxide layer begins to form when the sample approaches 300\(^\circ\)C and appears fully formed by the time the steel heats up to 500\(^\circ\)C. This indicates some amount of residual oxygen in the chamber. The oxide begins to dissipate as the sample temperature increases further and appears to be completely gone as the sample reaches 700\(^\circ\)C. The shaded region in Figure 3 corresponds to the presence of the oxide and the stages of the oxide layer formation are also shown in Figure 4.

4.1. In-situ Spectral Emissivity

The normal spectral emissivity, \(\varepsilon_{\lambda}\), is calculated from the intensity measured by the spectrometer,

\[
\varepsilon_{\lambda}(\lambda, T) = \frac{I_{\lambda}(\lambda, T)}{I_{\lambda b}(\lambda, T)}
\]

and is plotted in Figures 5 and 6 for temperatures ranging from 400\(^\circ\)C – 800\(^\circ\)C. The higher spectral emissivity observed during the heating coincides with the formation of the oxide film illustrated in Figure 4. Alloying elements such as Mn, Al, Si, Cr, segregate from the bulk material toward the surface and form selective oxides during annealing. The change of surface topography caused by
these oxides will also lead to variation in the spectral emissivity [2, 7]. Under the conditions of this experiment, based on the Ellingham diagram [18], one would expect to see manganese or chromium oxide form on the surface, and, since the oxide appeared to vanish over 700°C, it is most probably chromium oxide.

Figure 3. Thermocouple reading for the annealed DP980 sample showing the region of the observed oxidation.

Figure 4. Images of the coupon surface during heating. The sample surface is clean at the start of the experiment (a), but an oxide layer begins to form at ~300°C (b), becomes thicker (c), and is fully formed by ~500°C (d). The oxide starts to clear at ~600°C (e) and cannot be seen at ~700°C (f).
The spectral emissivity plotted in Figures 5 and 6, show that the spectral emissivity decreases with increasing wavelength. This is expected for metals observed in the infrared range. The spectral emissivity is highest at 400°C due to the oxide formation but decreases as the temperature increases and the oxide clears. The shorter wavelengths (< 2µm) are more impacted by oxide formation in comparison with the longer wavelengths. The spectral emissivity remains stable once the surface reaches 800°C, and the values of $\varepsilon_\lambda$ at the beginning and end of the soak period are indistinguishable.

Figure 5: Evolution of $\varepsilon_\lambda$ of DP980 coupon measured using the NIR spectrometer. Dashed lines correspond to pyrometer detection wavelengths.

Figure 6: Plots of $\varepsilon_\lambda$ as a function of (a) wavelength and (b) time/temperature.

4.2. Pyrometrically-inferred Temperature

We next investigate how the varying spectral emissivity affects the pyrometrically-inferred temperature, thus assessing the robustness of the pyrometry algorithms. The focus of this paper is to compare the accuracy of the pyrometrically-inferred temperature for the steady-state condition, i.e. the soaking period, where the effect of the surface oxide is minimized. In the case of ratio
pyrometry, the emissivity ratio, $\varepsilon_{\lambda_d}$ for the wavelength combinations indicated in Table 2 is obtained from the spectral emissivity of the as-received sample at room temperature shown in Figure 1. The inferred temperature is then calculated using Eqs. (6) and (7).

Table 2: Spectral emissivity ratio (e-slope) measured from the as-received DP980 sample

<table>
<thead>
<tr>
<th>Wavelength Combination</th>
<th>Emissivity Ratio, $\varepsilon_{\lambda_d}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ratio 1</td>
<td>1.6μm/2.4μm</td>
</tr>
<tr>
<td>Ratio 2</td>
<td>1.6μm/2.1μm</td>
</tr>
<tr>
<td>Ratio 3</td>
<td>2.1μm/2.4μm</td>
</tr>
</tbody>
</table>

For the multi-wavelength approach, the three exponential emissivity compensation algorithms listed in Table 3 are employed.

Table 3: Multi-wavelength emissivity compensation algorithms

<table>
<thead>
<tr>
<th>Emissivity Model</th>
<th>Mathematical Representation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model 1</td>
<td>$\varepsilon_{\lambda_d} = \exp\left( a_0 \lambda_d \right)$</td>
</tr>
<tr>
<td>Model 2</td>
<td>$\varepsilon_{\lambda_d} = \exp\left( a_0 \frac{\lambda_d}{T_{\lambda_d}} \right)$</td>
</tr>
<tr>
<td>Model 3</td>
<td>$\varepsilon_{\lambda_d} = \exp\left( a_0 \sqrt{\frac{\lambda_d}{T_{\lambda_d}}} \right)$</td>
</tr>
</tbody>
</table>

where $a_0$ is the algorithm constant and $T_{\lambda}$ is spectral radiance temperature, i.e. the equivalent blackbody temperature calculated using the measured spectral irradiance. The irradiance measured by the pyrometer at the three detection wavelengths ($p=3$) is solved simultaneously using non-linear least-squares regression to minimize the sum of squared errors given by

$$\chi^2 = \sum_{i=0}^{p} \left[ \ln(L_{\lambda,\text{meas},i}) - \ln(L_{\lambda,\text{gen},i}) \right]^2$$

where $L_{\lambda,\text{meas},i}$ is the measured spectral irradiance and $L_{\lambda,\text{gen},i}$ is the generated spectral irradiance that minimizes the sum of squared errors using the emissivity compensation algorithm.

Table 4 summarizes the performance of the pyrometry methods in terms of the maximum absolute error and the average relative error. The inferred temperature obtained as a function of time for both the ratio and multi-wavelength (MW) methods is displayed in Figure 7. The best estimator overall for the soaking period is MW Model 2. Although both methods over-predict the surface temperature, the multi-wavelength method provides a better estimate of the surface temperature in comparison with the ratio method. A similar analysis of the pyrometrically-inferred temperature for TRIP steel heated up to 850°C also showed over-prediction of the true surface temperature [3].
Table 4: Maximum absolute error and average relative error for pyrometry methods

<table>
<thead>
<tr>
<th>Pyrometry Method</th>
<th>Model</th>
<th>Max Abs. Error Soaking (°C)</th>
<th>Avg. Relative Error Soaking (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ratio</td>
<td>Ratio 1</td>
<td>32.40</td>
<td>3.57</td>
</tr>
<tr>
<td></td>
<td>Ratio 2</td>
<td>42.27</td>
<td>4.86</td>
</tr>
<tr>
<td></td>
<td>Ratio 3</td>
<td>8.48</td>
<td>0.45</td>
</tr>
<tr>
<td>Multi-wavelength</td>
<td>Model 1</td>
<td>16.76</td>
<td>1.37</td>
</tr>
<tr>
<td></td>
<td>Model 2</td>
<td>6.27</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>Model 3</td>
<td>37.85</td>
<td>3.99</td>
</tr>
</tbody>
</table>

Figure 7. Pyrometrically-inferred temperature for (a) ratio pyrometry and (b) multi-wavelength pyrometry.

For the ratio pyrometry methods, the best approximation during the soaking period was obtained for Ratio 3 (2.1μm/2.4μm). The greater precision observed for the 2.1μm and 2.4μm wavelength combination is most likely due to the proximity of the spectral bands to the region of emissivity consistency. As seen in Figure 5 and 6(a), the emissivity at wavelengths longer than 2μm experience the least variation with changing temperature and surface oxide condition. Tsai et al. [14] also noted that for five detection bands centered around 1.8μm, 2.18μm, 2.4μm, 3.5μm, and 4.5μm, the 2.18μm and 2.4μm produced the most accurate solution for ratio pyrometry.

4.3. Spectral Emissivity for Pyrometry Models

The performance of the pyrometry algorithm depends on the accuracy of the corresponding emissivity model. Figure 8 compares the $\varepsilon_\lambda$ measured by the spectrometer to the values assumed by the ratio pyrometry models, which are obtained by substituting the inferred temperature into Eq. (4). The plots show that ratio pyrometry models do not fully capture how $\varepsilon_\lambda$ changes with the evolving surface state. The MW models give a better approximation of $\varepsilon_\lambda$, as shown in Figure 9. For the MW models, the spectral emissivity was obtained by substituting the values of $a_0$ found by non-linear regression into the emissivity models in Table 4. The significant difference between emissivities predicted using Model 2 and Model 3 suggests that $\varepsilon_\lambda$ for DP 980 is best described by an exponential of linear first-order function of $\lambda$. Model 2 outperforms Model 1 because the former model accounts for the effect of the changing temperature in addition to wavelength.
5. Conclusion and Future Work

This study investigates the spectral emissivity for DP980 steel coupons annealed in 95% N₂/5% H₂ at a dew point of −40°C. Time-resolved spectral emissivity measurements are made in-situ using a near-infrared spectrometer and then compared to values inferred from a multi-wavelength pyrometer and a range of ratio and multi-wavelength pyrometry algorithms. The algorithms are also assessed for their ability to predict the coupon temperature. The spectral emissivity of the steel coupon varies strongly with the formation and dissolution of an oxide layer on the steel surface, especially at wavelengths less than 2µm. The most accurate ratio pyrometry predictions are obtained at the longest measurement wavelengths, 2.1 and 2.4µm. The temperature and emissivity measurements found with the multi-wavelength algorithms are generally superior. Future work will focus on eliminating the O₂ infiltration in the measurement chamber that causes the oxide layer to form.

These results highlight the fact that accurate pyrometry relies on an accurate emissivity model. Ongoing parallel research is focused on developing a theoretical foundation for predicting the connection between the evolving AHSS surface state and $\varepsilon_\lambda$, which will be incorporated into the pyrometry algorithms. Improved pyrometry algorithms pave the way for the next generation of high performance steels, which derive their mechanical performance, in part, from precise temperature control during processing.
Acknowledgments
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