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Research paper

A non-contact method for measuring temperature changes due to gas wiping of Zn alloy coatings produced on a continuous galvanising line

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ABSTRACT

Operando style, non-contact infrared thermography has been used to study the change in surface metal temperature between the zinc bath compared to just above the gas jet knives at an industrial, continuous galvanising line (CGL). Measuring photons in the wavelength range 7–12 μm at 30 frames per second (fps), the change in photon count was 4608. Using an emissivity of 0.069, corresponding to zinc, this correlates to a minimum temperature drop of 14 °C. Using higher emissivities, linked with oxidized surfaces, suggests an even higher temperature drop (up to 19 °C). These data are key in understanding the influence of coating weight processing parameters on continuously galvanised sheet steel with implications for surface finish, microstructural morphology and resultant corrosion resistance of the material. The infrared data is validated using static measurements of molten zinc and zinc dross between 430 °C and 470 °C in a hot dip galvaniser simulation pot containing 40 kg of molten GI (Zn 0.2 wt. %Al).

1. Introduction

The galvanising of steel is a key industrial process that significantly extends the lifetime of a range of products and infrastructure. The process involves applying a thin layer, in the range of 5 to 40 μm onto a steel substrate. In continuous galvanising, this can occur at speeds of up to 180 m/min. Coating weight is controlled by gas knives situated around 1 m above the molten bath surface. Processing parameters can influence the microstructure of the final coating and have consequences for mechanical and corrosion performance. This is especially the case with Zinc Aluminium (ZA) and Zinc Magnesium Aluminium (ZMA) galvanised coatings, which have become increasingly popular over the past two decades owing to their reported superior corrosion protection when compared to standard hot dip galvanised (HDG) coatings [1,2].

The final coating properties are due to their alloy additions, and a complex interplay of process parameters that govern the formation of the various phases during solidification. One of the main processing parameters is coating weight, which is controlled using gas jet wiping [3]. The wiping takes place <1 m from the liquid bath surface and is used to remove liquid zinc from the vertically emerging strip in a controlled manner. Gas jet knives blow nitrogen or air at the moving strip through a thin slot, typically <1 mm, from a distance of around 10 mm from the moving steel strip. If a thinner coating is required, higher gas pressure is applied, or the knife to strip distance is reduced, or both [4].

Cooling rates for the coating are critical in determining the final surface finish, microstructural morphology and resultant corrosion resistance. In ZA and ZMA coatings, higher cooling rates have been shown to result in smaller, more numerous primary zinc phase while slower cooling results in a courser microstructure. This can impact on the visual surface appearance of the strip and can dictate if the product is suitable for its intended end application.

However, there exists no accurate temperature measurement of the coating as it passes through the gas jet knives on an industrial galvanising line. Contact measurements cannot be used, since the strip is moving at speeds of up to 200 m/min, and any contact would make a mark on the still liquid coating, which would be unacceptable to the end user of the product. Traditional pyrometers have also struggled to provide accurate readings due to the high emissivity of the liquid zinc. Efforts to understand the cooling in the gas knives has been focused on modelling. Work by Elsaadawy et al. [5] predicts cooling from the knives to be in the region of 5 °C. However, assumptions of solidification

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points are made by eye and are only applicable to specific line conditions.

Metallographic evidence for cooling effects have been observed by Malla et al. [6] who studied the effect of coating weight on ZMA microstructure and found not only was there a significant change in phase morphology, but there was also a change in phase volume fraction. The thinner coatings (80 gm^{-2}) comprised of 15.97 % eutectic and 84.03 % primary zinc compared to 29.13 % volume fraction eutectic and 70.87 % primary zinc phase in the thicker (310 gm^{-2}) coatings. A change in volume fraction indicates a leaner coating chemistry with lower levels of Al and Mg. Given the coating is drawn from a pot of constant chemistry, this implies the coating process is influencing the composition of the final coating and cooled the zinc to a much higher degree than predicted by the models.

Similarly, work by Penney et al. [7] also observed change in phase volume fraction as a function of coating weight in the Zn 5 wt. % Al system which was also supported by measured changes in coating composition. This could theoretically be possible if during the wiping process, the cooling is sufficient to nucleate primary zinc dendrites on the steel surface leaving solute rich liquid to be removed by the knives back into the bath. At present, no methodology for measuring the cooling effect in the gas jet knives has been reported. In this study, thermal cameras were calibrated in laboratory conditions before being applied in an industrial continuous galvanising line. The research aims to elucidate the scale of cooling in the gas jet knives to validate microstructural effects already observed [6].

2. Experimental

The equipment used for thermographic monitoring was a FLIR A700 long-wave (7–14 μm) camera with an image resolution of 640 × 480 and a 24° lens. The thermal camera detected temperatures in the range of 0 °C and 650 °C. The image acquisition rate was set at 30 frames per second (fps). During the validation studies the FLIR A700 camera was mounted 0.54 m above and perpendicular to the surface of the liquid zinc in the experimental pot. The camera position was selected to minimise photon dispersion and absorption by the atmosphere but also to prevent the camera from overheating.

The temperature of the liquid zinc in the pot was ramped up incrementally and held at temperature points of interest which were monitored using thermocouples installed inside the pot. Due to the continual surface oxidation of the zinc coating, when these temperature points of interest were reached, scraping of the surface to reveal the unoxidized molten alloy was undertaken with a stainless steel blade. Oxidation of this nature is commonly recognised as increasing with alloying elements, such as the Al in the studied molten GI (Zn 0.2 wt. %Al), where selective oxidation occurs and aluminium oxide forms on the surface of the liquid Zn [8,9]. Using the FLIR Research Studio software, an oxide free window was then defined as a 1 cm^2 area with a uniform temperature profile which was selected for thermographic measurement determining unoxidized material emissivity at the temperatures of interest (Fig. 2c). To ensure the accuracy of the thermographic measurement, the ambient temperature and humidity were recorded using a combined sensor throughout the tests. This data was used to account for the energy of the additional photons contacting the sensor within the FLIR A700 camera. The date-time values from the thermocouple data were synchronised with the camera data to ensure emissivity was calculated for the correct temperature. In the validation experiments, the thermocouple data was compared with the infrared flux from the samples. However, FLIR Research Studio software was limited to an emissivity input at two decimal places, but this proved to be insufficient to return thermographic maps which accurately matched the thermocouple data. As a result, the data were exported to Excel (Microsoft) where linear interpolation (Eq. (1)) was applied to the data to recalculate emissivities to 3 rather than 2 decimal places thus reducing any potential error in temperature calculations by an order of magnitude [10]. Linear interpolation (Eq. (1)) calculates an unknown value between two points assuming a linear relationship, where T_0,e_0 and T_1,e_1 are the known coordinates and T is the known value of temperature and e is the unknown emissivity to be calculated.

$$\frac{e - e_0}{T - T_0} = \frac{e_1 - e}{T_1 - e_0} \tag{1}$$

There emissivity data were then used to calculate temperature for the in-situ measurements on an industrial continuous galvanising line.

Real time operando measurements were made at the Tata Steel Llanwern ZODIAC continuous galvanising line, which processes ca. 600,000 tonnes/y of coated steel. The focus was the temperature change of steel strip as it emerges from the liquid zinc alloy bath, with attendant surface oxide layer, and then upwards through two gas jet knives that control coating weight by removing excess molten zinc and as a result removes any surface oxide layer. The FLIR A700 was set 2 m away from the steel strip (Fig. 1) which gave a view of the liquid zinc bath, gas jet knives and zinc coating post gas jet knifes. During the measurements, the line was producing GI Hot Dip Galvanised steel on 0.6 mm x 1200 mm steel sheet with a target coating weight of 275gm^{-2}. GI is an acceptable coating alloy (0.2 wt. %Al, remainder Zn) to examine the cooling effects of gas wiping and has a more homogenous chemistry compared with more complex ZMA and ZA alloy coatings. Therefore, temperature changes measured on this alloy as a function of gas wiping can be assumed to be relative to those observed in ZMA alloys containing ~ 2 wt. %Al, 2 wt. %Mg remainder Zn and will be explored in more detail in future work.

FLIR Research Studio software (Teledyne FLIR LLC) was used to extract the temperature data from the operando measurements, by selecting the whole area of the sample in a 1100 pixel (18cm^2) rectangular area in each region of interest.

3. Results and discussion

3.1. Emissivity and validation studies – specialized melting pot

Thermal imaging was undertaken to determine the change in temperature of the Galvanised (GI) coating at a continuous galvanising line (CGL) process from the hot-dip galvanising bath to approximately 30 cm after the gas jet knives. Surface temperature measurements can be classified into contact and non-contact methods [11]. The IR thermal imaging technique used in this study is non-contact, in order to enable material temperature measurements to be recorded where thermocouple measurements are not feasible. This is particularly useful in continuously moving industrial processes, such as the CGL process, where physical contact between a thermocouple and the metal surface would alter the surface physically or chemically [12]. To measure dynamic material temperature, the emissivity value used in data processing must also be dynamic as this value changes with material temperature, oxidation and phase changes [13]. To enable an appropriate emissivity to be used in the operando measurements, validation experiments were undertaken to determine the emissivity values required for unoxidized (i.e. metallic) zinc coating at a range of temperatures.

During the laboratory validation tests, the emitted infrared photons and spectral emissivity of the molten zinc alloy (Zn 0.2 wt. %Al) were determined by thermal imaging and validated with thermocouple temperature measurements. Hot dip galvanisation typically operates at a bath temperature of 460 °C with deviations of ±15 °C [14]. Therefore, in this validation study, the molten zinc alloy was heated using an electrical heating element in a specialised melting pot (Fig. 2a and b). The initial temperature of the pot was set at 430 °C and ramped up to 455 °C to provide a range encompassing the 5 °C drop in temperature from bath to post knives modelled by Elsaadawy et al. and greater temperature drops indicated by microstructural changes observed by Malla et al. This provided emissivity data across the key operational

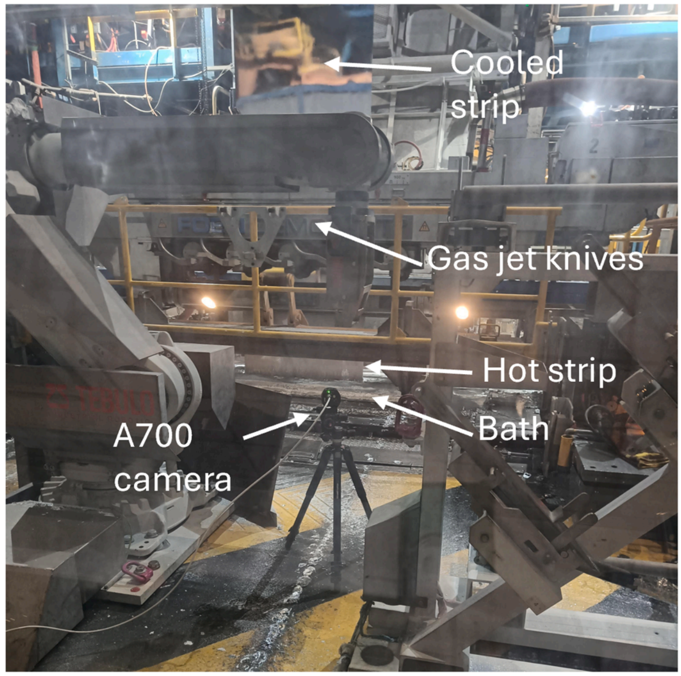

Fig. 1. FLIR A700 camera positioning to measure photon counts during the hot-dip galvanising (CGL) process at the Tata Steel Llanwern ZODIAC galvanisation line, encompassing the hot-dip galvanising bath and post gas jet knife zinc coating.

temperature range to analyse zinc coating temperature change at the Tata Steel Llanwern ZODIAC galvanisation line when no contact temperature measurements were possible.

Once data from the A700 had been imported into FLIR Research Studio the emissivity of the selected area was calculated through linear interpolation (Eq. (1)) by comparing the camera temperature to the temperature of the thermocouple and adjusting the emissivity to match the thermocouple temperature.

During the validation tests using the specialized HDS melting pot, emissivity values for the galvanising zinc were an average of 0.069 for temperatures between 455 °C and 430 °C (Fig. 3). This temperature range was selected to encompass the potential range of temperatures seen post knives on the CGL. The emissivity for this temperature range was calculated for the HDS melting pot in the absence of oxidation due to the scraping of the surface of the alloy material using a stainless steel blade to reveal the unoxidized molten alloy. This unoxidized surface provided an emissivity value that could be used to ascertain the temperature of the unoxidized alloy in the post knife region of the CGL process. As such, Fig. 3 shows that using an emissivity value rounded to 2 decimal places suggested by the FLIR software (i.e., either 0.07 or 0.06) is not sufficiently accurate to represent the temperature values measured at these temperatures and for this material. Hence, we have used 3 decimal place emissivities for the in line, operando measurements in the following section.

3.2. Operando study of industrial continuous galvanising line

Industrial experiments were performed on a continuous galvanising line. The FLIR A700 camera was used to analyse the temperature changes taking place to the surface of steel strip as it passes through a liquid zinc bath, picks up a thin layer of liquid zinc and then passes through nitrogen gas jet knives which blow excess zinc vertically downwards back into the zinc bath. So that any cooling effect of the knives could be measured, the surface was imaged at two positions, the liquid zinc bath and directly above the gas jet knives.

In these experiments, the FLIR A700 camera measured the intensity of infrared photons emitted in the wavelength range 7–12 μm. The photon flux in this wavelength range is recorded within each pixel to create the thermogram image. The photon flux recorded can then be converted into temperature by considering the emissivity of the material under study. In this study, the key material under study is the galvanic layer which is predominantly zinc with around 0.2 wt % Al. However, the situation is complicated by two additional factors; firstly, the zinc is applied to the steel surface as a liquid (i.e., above its melting point of 419.5 °C) and it solidifies during processing and, secondly, the zinc surface will oxidize when exposed to air such as when it is in the bath. So, bearing in mind that the infrared photons being measured in these experiments will have been emitted from the immediate surface under study, there are potentially three different materials to be included when considering a value for the emissivity to be used: namely liquid zinc, solid zinc and metal oxide.

Emissivity is the ratio of the energy emitted from (or absorbed by) the surface of a material relative to a perfect blackbody emitter at the same temperature and wavelength with 0 being a perfect reflector and 1 being a perfect emitter. The issue for galvanic zinc layers is that it has been reported that not only does the emissivity of newly deposited material change very substantially from ca. 0.10 to > 0.65 in a stepwise manner between ca. 400 and 500 °C but also there are substantial differences between new and aged material [15]. In addition, emissivity values of up to 0.90 have been reported for zinc oxide [16], and up to 0.32 for aluminium oxide [17] at the 8–14 μm spectral range

In the analysis of the data for the Zodiac CGL, temperatures of the molten zinc coating bath were calculated using an emissivity of 0.230 to replicate the value used by Elsaadawt et al. [5]. A bath emissivity of 0.230 is as a result of the molten alloy composition but importantly also as a result of the oxidized surface layer of the material. Despite the use of a drossing arm to remove oxidized material layers at and below the surface of the material the oxidisation of the surface layer occurs rapidly effecting emissivity values. Using an emissivity of 0.230, the surface temperature of the molten galvanising alloy, as determined by thermography, was 457 °C (Fig. 4b). Simultaneously, the temperature recorded at the Tata Steel Llanwern ZODIAC line by thermocouple was 458 °C thus demonstrating the accuracy of the thermal imaging and emissivity (Fig. 4b inset).

The area selected to undertake the thermographic mapping for the post gas jet knives galvanised zinc was selected to avoid any interference

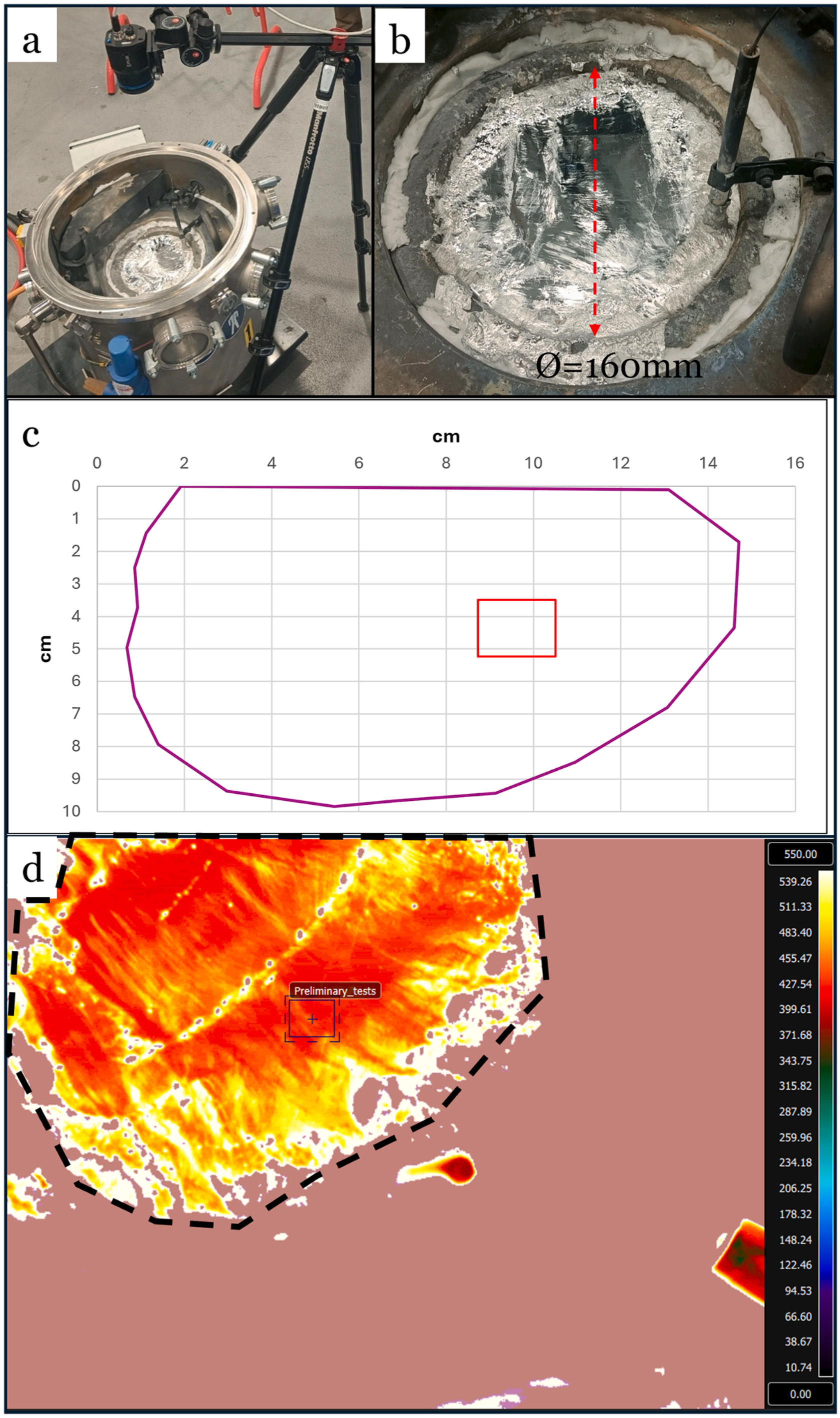

Fig. 2. (A) a schematic showing the heating tests with the location of the camera, (B) the surface of the zinc alloy in the melting pot showing the visual differences in surface texture and reflectivity, (C) scaled areas analysed in FLIR research studio for the heating tests. Red = Measured 800 pixels, 1 cm^2, purple = bounds of de-drossed liquid zinc coating, (D) thermal image of the melting pot where the yellow and orange section represent the de-drossed zinc with the oxide coating removed and the solid maroon area the dross.

from external sources such as the strip stabilising magnets adjacent to the steel strip which can be seen increasing the recorded counts, and as such interfering with temperature analysis, denoted by the yellow colour next to the red of the selected area of the post gas jet knives galvanized zinc on the thermographic map (Fig. 4a). For data analysis here, an emissivity of 0.069 was used for the unoxidized zinc coating post gas jet knives to replicate the emissivity from unoxidized zinc calculated in the validation study alloy giving a value of 444 °C (ESI Table 1). Post gas jet knives oxidation on the surface of the material has been removed by the gas jet knives in an equivalent manner to the scraping of the surface of the alloy in the HDS pot which revealed unoxidized molten alloy during validation studies. This enables the emissivities calculated in the validation study to be utilised to determine post air knife alloy temperature. The change in temperature from the liquid zinc coating bath and the zinc coating post gas jet knives was then calculated by subtracting one from the other to calculate a drop in temperature of 14 °C from the liquid galvanising zinc hot dip bath to the galvanising zinc post gas jet knives. This temperature drop is also

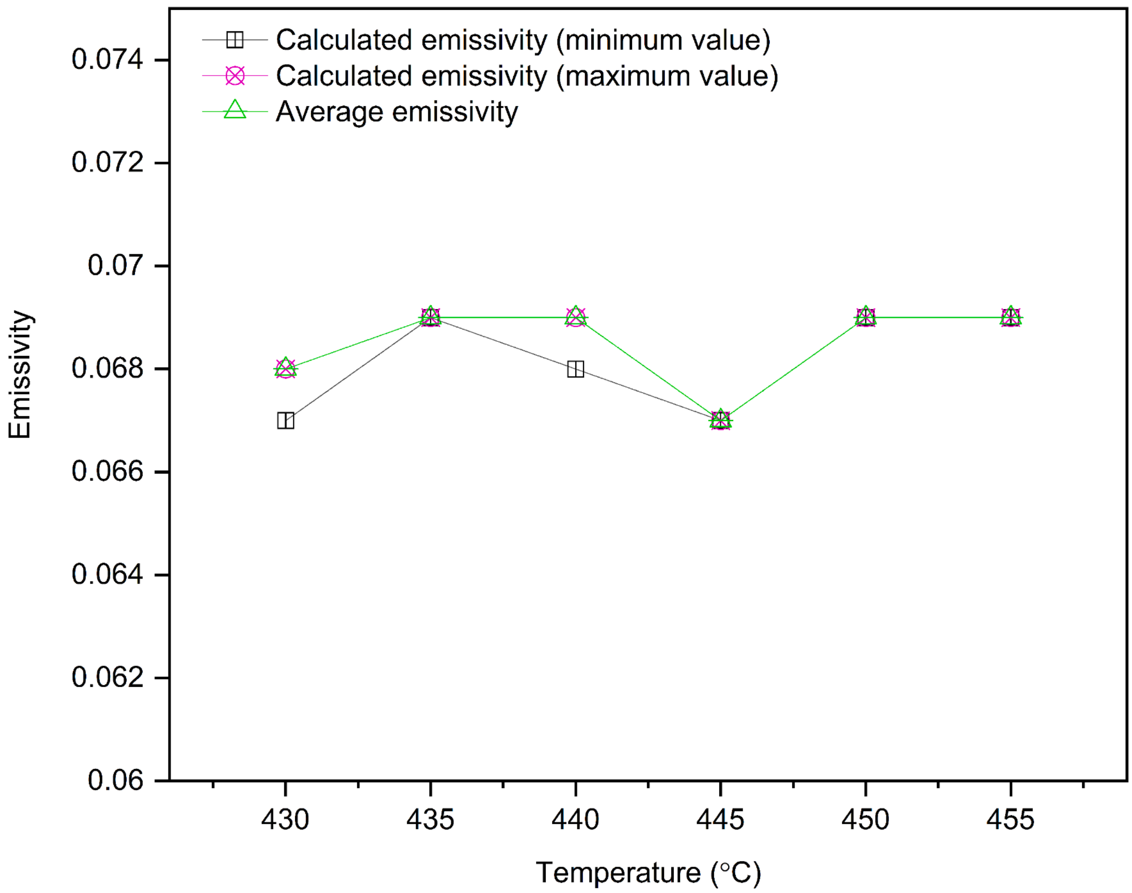

Fig. 3. The calculated emissivity of the zinc alloy in the specialised melting pot measured by the A700 camera.

supported by previous experimental studies of changes to the microstructure in the materials studied [6,7]. A temperature drop due to the action of the gas knifes could decrease wiping efficiencies if the bath temperature is close to the melting point of the coating alloy. In GI type coatings, which have a homogeneous single-phase microstructure with no mushy zone, the effect of cooling below the solidification temperature during wiping does not cause any microstructural changes but may lead to an increase in viscosity and a drop in wiping efficiency. This is unlikely to happen in modern continuous galvanising lines which operate with bath temperatures around 460 °C and are very well controlled. In multiphase coating alloys such as 5wt % Al and ZMA alloys containing >1wg %Al and Mg respectively, cooling in the gas knives can have microstructural implications [6,7]. Upon freezing, these alloys first exhibit a Zn plus liquid phase (mushy zone). If the cooling in the knives is sufficient to lower the temperature into this two-phase region, then solute rich liquid will be wiped back into the bath leading to a chemistry change in the final coating. In low coating weights, the gas knife pressure is significantly increased compared to the conditions described in the $275gm^{-2}$ coating described in this research, meaning greater cooling is expected. Therefore, the real-life implication of this research when processing low coating weights in multiphase coating alloys is that the final coating chemistry differs from the bulk bath chemistry, as observed by Malla et al. and Penney et al. These chemistry changes result in an altered microstructure which in turn influences the corrosion resistance of the final product.

In further support of the 14 °C temperature drop measured in this study, using the standard two decimal place emissivity suggested by the FLIR software, (i.e., 0.07) the thermographic mapping presents a temperature post gas jet knives of 439 °C, which is a drop of 19 °C from the molten bath temperature. Furthermore, studies by Elich and Hamerlinck [15] discussing the emissivity of galvanized steel over a temperature range have suggested that an emissivity of 0.10 or higher should be used for galvanising zinc at a temperature of ca. 440 °C (ESI Fig. 1) an emissivity value also referenced by Elsaadawy et al. [5]. However, using an emissivity of 0.10 doesn't take changes in oxidization as seen between the bath and post air knives into account and would increase the drop in temperature from bath to post knives to ca. 111 °C, a value far beyond what is suggested by the micro chemistry changes in the material. A temperature drop of this magnitude would also lead to complete solidification of the coating within the gas jet knives.

The complexity of this industrial process is apparent in Fig. 4b, where, despite the use of the robotic drossing arm removing oxidized material from the surface of the molten zinc alloy, it is apparent that the infrared emission from the surface is not homogeneous and oxidized material is evident across the surface layer. So, whilst the majority of the area can be seen as orange in the thermographic mapping, denoting a temperature of ca. 457 °C in line with the thermocouple, there are areas which were obviously green in the thermography indicating a larger degree of oxidization. These areas were not used to determine the temperature of the liquid galvanising zinc. In the thermographic mapping the area directly above the bath is the steel strip emerging from the bath and prior to being subjected to the gas jet knives. This area showed evidence of a curtain effect whereby the excess liquid galvanising zinc flowed back down the steel sheet creating a material with a variety of thicknesses, texture and oxidation states (Fig. 4b). Surface roughness and homogeneity are important factors in emissivity and therefore temperature measurement [18,19], the area post gas jet knives is smooth, non-flowing, metallic and consistent, which allows for more accurate data capture.

The model proposed by Elsaadawt et al. [5] suggests that heat transfer within 0.5 m of the knives is dominated by convective cooling whilst radiative cooling significantly increases with distance away from

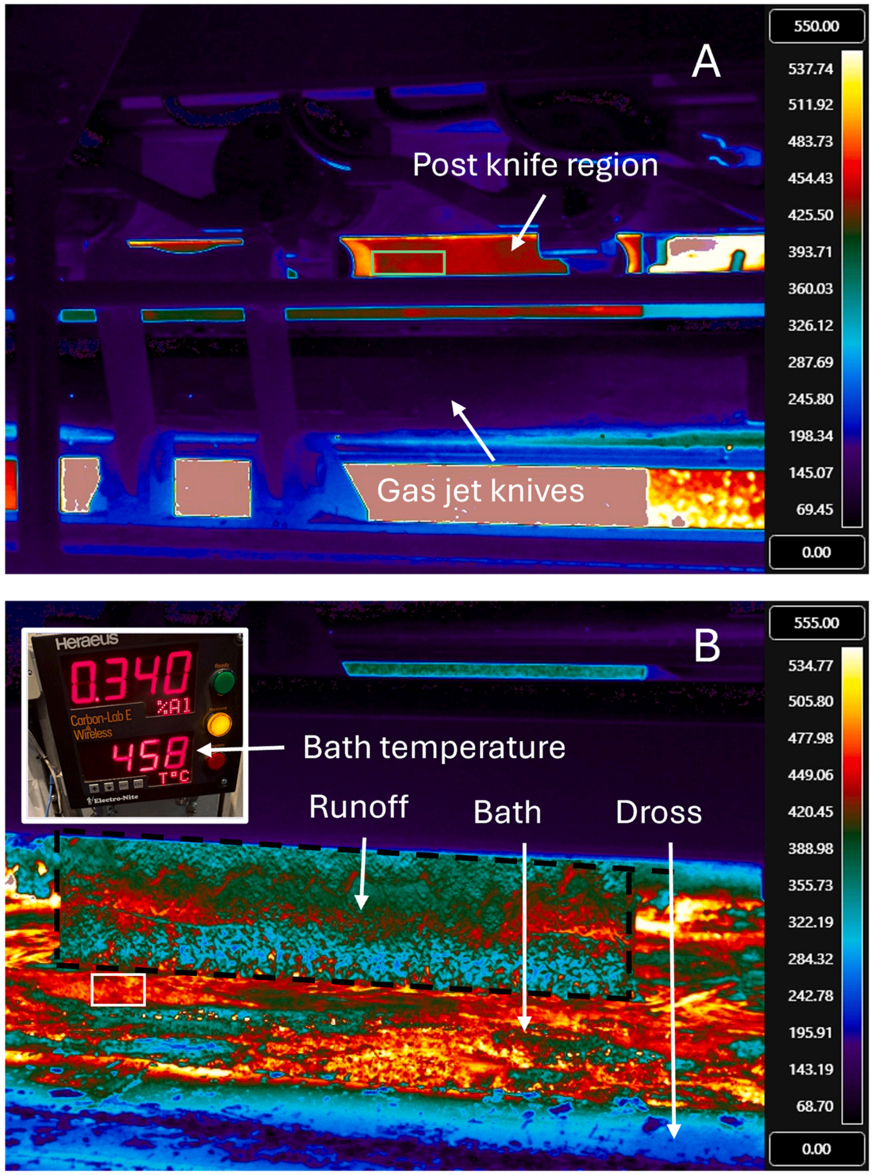

Fig. 4. FLIR A700 thermographic maps of the continuous galvanising line showing (A) the region above the gas jet knives where the galvanised zinc temperature measurement is denoted by the green box labelled "Post knife region" and (B) the molten zinc bath temperature measurement is denoted by the white box and pre gas jet knives galvanising zinc areas with zinc runoff is denoted by the black dotted box (inset) ZODIAC temperature gauge of the hot-dip galvanising bath.

the gas jet knives. Additionally, the Elsaadawt et al. simulation used emissivity as a modifier for the ratio of radiative to convective heat flux. Hence, an emissivity change from 0.23 to 0.10 was shown to vary the dry line distance from the knives (defined as the point where 80 % of the zinc coating had solidified) by only 10 % indicating minimal variation in post gas jet knife temperature. Uncertainty may be introduced since a change in visual appearance has been used in the simulation to denote a change in emissivity and vice versa, thus creating a cyclic argument. Given the substantial emissivity changes with zinc temperature, this makes accurate temperature simulation very challenging. Furthermore, the model does not take into account possible solidification and remelting in the knife region. The steel sheet will hold residual heat as it emerges from the bath so could potentially remelt the zinc layer adjacent to the steel strip and not be obvious to the human eye.

However, when using the non-contact infrared camera to measure temperature, only the photon flux is measured. This is then converted into temperature via the emissivity which is a complex function of temperature and chemistry independent of the heating or cooling. Therefore, the experimental data can vary compared to the simulation. An example of this is that the starting temperature is not affected by the change in emissivity in the simulation study (Figure 15 in [5]). In addition, the emissivity value of 0.23 is representative of the far jet region which has a more substantial radiative flux away from the surface and is applicable to the bath conditions that are at steady state. By comparison, an emissivity value of 0.10 is more usually used as the dynamic value, which is much closer to the value of 0.069 used in this study.

Lower values of emissivity in line with a reduction in temperature, in this case a reduction in emissivity from 0.23 to 0.069, is a recognized phenomenon [11,12,20]. The emissivity of metals can be seen to change significantly over small temperature changes, often due to phase change in what is considered a transition region, oxidation changes, or roughness changes, before becoming stable [11,20,21] (ESI Fig. 1). Pristine, unoxidized, zinc metal has a low emissivity because, when its density of states is calculated [22], the data show a broad but isolated ground state band which is typical of a metal conductor. In metallic zinc, this band is fully occupied with electrons, which makes the probability of radiation absorption or emission very low. Thus, heating (or cooling) zinc will be much more efficient by conduction. In a continuous galvanising line, there will be a conductive cooling affect because of the gas jet knives used to blow nitrogen gas towards the moving strip from both sides to remove excess zinc and attendant oxidized outer layers. The heat capacity of nitrogen is 26.7 J/mole.K at ca. 25 °C [23]. To put this value into context, CO_2 gas is widely used as a heat transfer agent and has a heat capacity of 37.1 J/mole.K [24]. This suggests that N_2 will absorb heat from the strip surface in the gas jet knives by conduction. Assuming a strip width of 1200 mm strip and a N_2 flow rate of 2200 Nm^3/h [25]. This corresponds to 2618 kg/h or 93,500 mol of N_2/h which in turn corresponds to 2496.5 kJ of energy transfer from the strip to the N_2 per degree Kelvin per hour (or 41.6 kJ/K/min). So, if the N_2 increases in temperature by 20 K, this is 832 kJ/min or 13.9 kJ/s, which is a substantial cooling effect. In addition, the use of flowing gas at the gas jet knives creates a nitrogen blanket at the zinc surface on the line material, which limits oxidation. Firstly, this is evidenced by the absence of dross on the line material as compared with the widespread metal oxide-based dross on the surface of the zinc bath material. Additionally, the dross is physically moved by the nitrogen blown over the emerging strip by the gas jet knives, this process is desired by galvanisers since it keeps the pool clear as the strip emerges. The absence of oxidation on the strip is also evidenced by the highly consistent thermal response from the line surface material, i.e. it is all emitting in the same way because it is all the same material. The zinc has two surfaces, the outer surface exposed to nitrogen gas and the inner surface which is interfaced to the steel substrate. Here, the strip is heated to ca. 5 °C hotter than the zinc bath to enhance coating adhesion. Heat will be transferred across the temperature gradients at both surfaces by conduction to the adjacent atoms (predominantly iron atoms at the inner surface and N_2 gas at the exposed surface) and by the radiative losses which in this paper are also used to study the process.

4. Conclusions

Gas wiping is a critical part of the continuous galvanising process and temperature changes during the process can influence product quality as well as coating mechanical and corrosion performance. Previous studies relating to the change in surface metal temperature between the zinc bath compared to just above the gas jet knives at an industrial, continuous galvanising line (CGL) have focused on modelling temperature reductions. This study utilised more accurate non-contact thermography, based on validation experiment emissivities, to determine a minimum temperature drop between Zn bath and cooling knives of 14 °C, higher than the 5 °C drop modelled in previous work. This increased cooling can have microstructural implications as if the temperature reduction in the knives is sufficient to move into the two-phase region, then solute rich liquid will be wiped back into the bath resulting in a chemistry change in the final coating. The difference in the minimum 14 °C cooling observed in this study of a target coating weight of 275 gm^{-2} to the 5 °C cooling modelled by Elsaadawt et al. can further be explained by considering the role of conductive cooling as a result of the nitrogen blown at the metal surface by the gas jet knives to remove excess zinc. This process also creates a nitrogen blanket preventing oxidation of the material as evidenced by the absence of dross on the line material as compared with the widespread oxide-based dross on the surface of the zinc bath material and by the highly consistent thermal response from the line surface material post gas jet knives.

Data availability

Select images are available in the electronic supplementary information, further images from the thermal camera are available on request from the corresponding author.

CRediT authorship contribution statement

Stuart Cairns: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **David Penney:** Writing – original draft, Conceptualization. **Sam Reis:** Writing – original draft, Methodology, Formal analysis, Conceptualization. **Anthony Lewis:** Writing – review & editing, Methodology, Formal analysis. **James Sullivan:** Writing – review & editing. **Oliver Newton-Coombs:** Writing – review & editing. **Clive Challinor:** Writing – review & editing. **Peter J. Holliman:** Writing – original draft, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Stuart Cairns reports financial support was provided by Engineering and Physical Sciences Research Council. Peter Holliman reports financial support was provided by Engineering and Physical Sciences Research Council. Anthony Lewis reports financial support was provided by Engineering and Physical Sciences Research Council. Sam Reis reports financial support was provided by Engineering and Physical Sciences Research Council. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.rineng.2026.110447.

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