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Effect of a moving flame on the temperature of polymer coatings and substrates

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ABSTRACT

A computational model is developed to predict the temperature profile over an organic coating on a metal surface as a result of the action of a moving flame. The deflection of the flame as it impinges on the surface is simulated and its consequent heat transfer to the polymer is determined. The scanning action of the flame across the substrate is quantified and the temperature profiles within the polymer are calculated. The results show a substantial build up of temperature at the surface and large temperature gradients throughout the thickness, which are due to the low thermal conductivity of polymers. This can be particularly detrimental for polymers owing to their low softening and decomposition temperatures. The model can be applied to flame impingement on a bulk polymer or on an organic coating on a metal substrate. The research shows the risks of a moving flame overheating a polymer surface and indicates remedial measures.

1. Introduction

Thermal spraying has been increasingly used for the deposition of polymer coatings, such as ethylene vinyl acetate and ethylene vinyl alcohol copolymer [1], polyethylene [2], fluoropolymer PVDF, ECTFE, PFA and FEP [2,3] and PEEK [4]. In thermal spraying, there is an interaction between the heat source and both the deposited coating and substrate. The interaction may have a significant effect on the quality of the deposited coatings and has attracted widespread attention for reasons of process control. For example, Xia et al. have experimentally investigated the effect of processing parameters on the temperature profile in the coating and substrate during plasma spraying [5]. This effect is more important when temperature-sensitive materials such as hydroxyapatite and polymers are used as coating materials [6]. Overheating of polymer surfaces is a frequent danger both in their use in engineering applications and in their production. The overheating can lead to degradation of the polymer and possibly the evolution of hazardous gases. Flame impingement on organic surfaces can occur in polymer processing, heat treatment or coating deposition.

Polymers with their decomposition temperatures as low as 250 °C are particularly sensitive to flame impingement. Another unique but less obvious characteristic of polymers is their extremely low thermal conductivities, which can be three orders of magnitude below those of common metals. This results in a very slow flow of heat away from the hot surface zone and as a consequence, the temperature of the outer surface of the polymer remains high during flame impingement. This clearly exacerbates the problem of maintaining the temperature of the polymer below its decomposition temperature [7–10].

This paper uses heat transfer theory, fluid mechanics and computational methods to simulate the temperature profile over the surface of an organic body or coating. The model identifies the critical parameters, such as scanning rate, flame power and polymer thickness, and predicts their influence on temperature profiles during impingement due to a moving flame.

2. Experimental details

2.1. Materials

The materials system considered was a polyethylene coating on a low-carbon steel substrate. The coating thickness was typically 0.2–1.0 mm and the steel thickness was 1.0 mm, although these dimensions were varied in the investigation. The substrate geometry consisted of a flat square sheet or panel of side 100 mm. This organically coated steel was subjected to impingement by a moving flame as described below.

2.2. Flame impingement

The organic surface was scanned with a combustion flame gun using acetylene as a fuel gas with a flow rate of 6.5 standard litres per minute (SLPM). If full combustion takes place, the power provided is 6.1 kW. The distance between the gun nozzle and the polymer surface was fixed at 200 mm for all tests. The flame was

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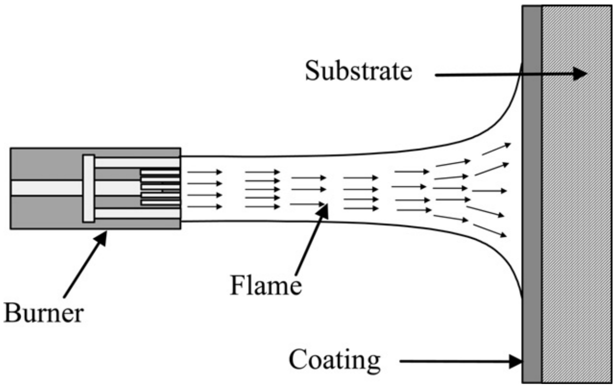

Fig. 1. Schematic of a flame impinging on a polymer.

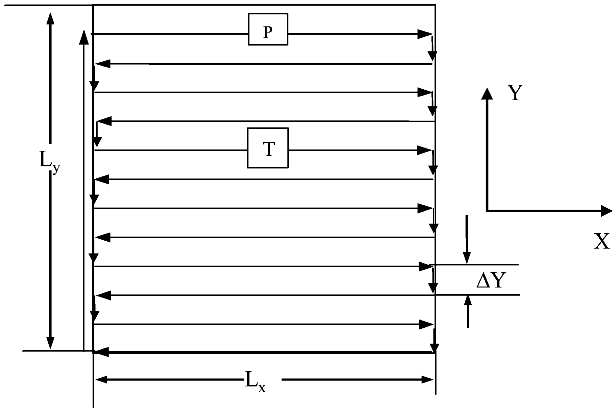

Fig. 2. Schematic of a flame scanning over a polymer surface.

scanned over the surface in a regular pattern. It commences with a horizontal sweep or pass at the top edge of the sheet from left to right, a vertical step downwards, a return pass from right to left, another vertical step down and so on until bottom of the sheet is reached. At this point in time, the entire front of the sheet has been exposed to the flame and this is designated as one scan. On the other hand, a single sweep of the flame gun from left to right (or vice versa) is designated as one pass. The flame gun then returns to the top of the sheet and the scanning action repeated. The scanning speed was set at 160 mm/s and the vertical step between each horizontal pass at 7 mm. It required 16 passes and 10 s to cover the entire face of the substrate from top to bottom and finish one scan. The temperatures at the surface of the polymer coating and back of the substrate were measured and recorded.

2.3. Temperature measurement

The temperature of the flame was measured by using a type R thermocouple protected by a ceramic tube with an open head. The thermocouple tube was held on an *x*–*y* two-dimensional travel unit so that the axial and radial temperatures of the flame could be measured. To measure the effect of substrate on the temperature profile of the flame, a substrate of 100 mm × 100 mm was placed in front of the flame at a distance of 200 mm from the nozzle exit. The temperatures at the back of the substrate and at the front of the coating were measured with an infrared thermometer (MX4 CF Infrared Thermometer, Raytek, UK), which has a response time of 0.1 s. The data collection was set at 0.1 s so that 10 readings were recorded on computer each second.

3. Computational model

3.1. Configuration

The movement of the flame over the organic surface is shown schematically in Fig. 1. The flow of the gas jet as it impinges the substrate surface is important for the transfer of heat from the hot gas to the surface. A stagnation point is formed above the solid surface and normal to the impingement. The gas escapes by flowing out to the sides in a radial manner. The significance of the fluid flow is that the polymer does not experience the flame as a concentrated beam but as a diffuse flow of hot gas over its surface in which the gas velocity and temperature gradually decrease with distance from the flame centre. These characteristics govern the heat transfer coefficient and the rate of heat transfer, which will be discussed later.

The scanning pattern used in this investigation is represented in Fig. 2: a horizontal action with a vertical step between individual passes. When the torch reaches the bottom of the sheet, it returns to the top and repeats the scanning path. Although the axial (horizontal) distance between the nozzle exit and the substrate (the stand-off distance) is fixed, the radial (vertical in Fig. 2) distance from the central axis to any position of the substrate varies during the movement of the flame as a consequence of the scanning action shown schematically in Fig. 2. The variation of this radial distance is a function of the scanning pattern, the size of the substrate and the torch scanning speed. For a fixed point on the substrate, the exposure time, t_e, can be expressed as:

$$t_e = \frac{d}{v_s} \tag{1}$$

where d is the diameter of the flame and v_s is the scanning speed of the torch. For a square-shaped substrate, the scan has two-dimensional symmetry and the time interval, t_{it}, between rescanning for a given elemental area can be expressed as:

$$t_{it} \approx \frac{A}{A_f} t_e = \frac{A}{d^2} \frac{d}{v_s} = \frac{A}{d v_s} \tag{2}$$

where A is the area of the substrate and A_f is the cross-section area of the flame. A lengthy time between scans, t_{it}, reduces the heat input into the substrate. Eq. (2) shows that t_{it} can be decreased by reducing the workpiece area and/or raising the scanning rate. However, increasing the scanning rate will reduce the exposure time (Eq. (1)), which reduces the heat input to unit area in unit time and thus also reduces the rate of temperature rise. As a result, increasing the scanning rate has two opposing effects on the heat input to the substrate.

The scanning rate of the flame as it moves across the polymer surface affects the heat transfer rate as well as the temperature experienced by a given elemental area of the substrate. This will significantly influence the heat transfer from the flame to the polymer. In order to simulate the heat transfer, therefore, the temperature profile and the heat transfer coefficient of the flame to the polymer must be pre-defined. In early research, the situation was simplified by describing the temperature distribution of an impinging jet in the radial direction by a Gaussian distribution. However, this is only valid for a free jet whereas in the present study, the flame impinges on a solid body. The temperature distribution of the flame in this case was directly measured as a function of radial distance from the centre of the flame and was used as a boundary condition in the computer model. Martin [11] and Shimizu [12] have carried out experimental work to measure the heat transfer coefficient of a jet impinging onto a plate. The heat transfer coefficient may be expressed as a function of distance from the axis of the jet as:

$$\frac{\mathrm{Nu}}{\mathrm{Pr}^{0.42}} = G\left(\frac{r}{D}, \frac{H}{D}\right) F(\mathrm{Re}) \tag{3}$$