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Process modelling of thermal spraying for thermoset coatings

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ABSTRACT

Thermal spraying has the ability to coat large components and structures on site. It has been used to deposit thermoplastic coatings but little work has been done on thermosets. To form a thermoset coating by thermal spraying, the feedstock particles have to melt in the flame without degradation but also the coating itself must then be cured by the end of the deposition process. The particle residence time in a typical thermal-spray flame during deposition is less than 0.01 s, whereas conventional thermoset powders need orders of magnitude more time at the baking temperature to achieve a sufficient degree of cure. However, the freshly deposited coating also receives heat from the scanning flame during thermal-spray deposition, which should contribute to the curing process. This effect is complicated by the fact that the heat input during scanning varies with time. To control the curing process, therefore, a full understanding of the interaction between the flame, coating and substrate is essential. In this paper, experimental trials and computer simulations were carried out aimed at controlling the temperature profiles of the thermoset deposit to enable sufficient cure to take place. Software developed by the authors was used to simulate flame scanning and post heat treatment. Commercial software was also applied to simulate steady-state infrared heating. The results indicate that process parameters have a critical effect on the properties of the coatings and can be optimized with the aid of computer simulation.

1. Introduction

Organic coatings are widely applied to protect metal components and structures throughout all industrial, construction and domestic sectors [1,2]. Despite the fact that the coating is the order of only 5% of the total cost of a structure, the choice of the most effective coating is a key factor governing its life [3]. Thermosets are by far the most commonly used type of polymer for coatings because of their superior strength, adhesion and chemical stability over thermoplastics. Thermal spraying has been increasingly used for the deposition of thermoplastic coatings, such as ethylene vinyl acetate and ethylene vinyl alcohol copolymer, polyethylene, fluoropolymer PVDF, ECTFE, PFA, and PEEK [4–7]. However, little work has been done on deposition of thermoset coatings largely because their deposition is much more difficult than that of thermoplastics. To form a thermoplastic coating by thermal spraying, thermoplastics have only to melt in the flame without degradation and then flow into splats on impact with the substrate. In the case of thermoset coatings, however, the particles have not only to melt in the flame to enable flow on impact with the substrate but also the resulting aggregate of splats or coating must then be cured by the end of the process.

The interaction between the heat source, deposit and substrate during thermal spraying has a significant effect on the quality of the final coatings and hence has attracted widespread attention for reasons of process control. For example, Xia et al. [8] have experimentally investigated the effect of processing parameters on the temperature profile in the coating and substrate during thermal spraying. This interaction is more important when temperature-sensitive materials such as hydroxyapatite and polymers are used as coating materials [9]. Sufficiently heating but without overheating the polymer surface is a challenge for the deposition of thermosets by thermal spraying. The overheating can lead to degradation of the polymer and possibly the evolution of hazardous gases. On the other hand, increasing the temperature of the coating will benefit the curing of deposited material.

The thermal conductivity of polymers is orders of magnitude lower than that of metal substrates. For example, the values for epoxy, nylon and steel are $0.19\,W\,m^{-1}\,K^{-1}$, $0.24\,W\,m^{-1}\,K^{-1}$ and $51.9\,W\,m^{-1}\,K^{-1}$, respectively. This results in a slow heat flow away from the hot surface zone and as a consequence, the temperature at 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 during deposition [10–13]. Another consequence of the poor thermal conductivity is a large temperature gradient in the coating and for a thermoset, this can cause non-uniform curing. One of the

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Nomenclature

C_p	specific heat coefficient (J kg^{-1} K^{-1})
D	diameter of nozzle (mm)
D_y	step size in y direction (mm)
h	heat transfer coefficient (W m^{-2} K^{-1})
H	distance from nozzle exit (mm)
ΔH	melting or curing enthalpy (J kg^{-1})
k	thermal conductivity (W m^{-1} K^{-1})
L_x	width of substrate (mm)
L_y	length of substrate (mm)
n	number of steps travelled in y direction
Nu	Nusselt number
Pr	Prandtl number
q	net heat flux to the surface of coating or substrate (W m^{-2})
R	radial distance to the centre of the flame (mm)
Re	Reynolds number
t	time (s)
t_x	travelling time in x direction during each scan (s)
T	temperature (K)
Tr	melting/solidification temperature range (K)
v_x	scanning velocity in x direction (mm s^{-1})
Z	coordinate in the direction perpendicular to surface
ρ	density of coating or substrate (kg m^{-3})
φ	thermal diffusivity (m^2 s^{-1})
ν	kinematic viscosity (m^2 s^{-1})

potential solutions to overcome this problem is to post-heat the coating after deposition by flame scanning or infrared irradiation.

This paper develops a computational model using heat transfer theory, fluid mechanics and computational methods to simulate the temperature profile in the coating and substrate during flame scanning and post heating using infrared heating. The effect of critical parameters such as heating power, coating and substrate thicknesses on the temperature profiles are investigated in this study.

2. Materials and parameters used for process modelling and validation

2.1. Materials

The materials system considered in the validation was an epoxy (Interpon AF, Akzo Nobel) coating of 1 mm thick on a substrate of a low-carbon steel sheet of 2 mm thickness and dimensions of 100 mm by 100 mm. Experimental tests showed that the materials could be fully cured at 200 °C. The polymer coated steel sheet was subjected to heat by the impingement of a moving flame as described below.

2.2. Heating

The polymer 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). Compressed air was used as a source of oxygen, cooling and carrier gas. The thermal power generated by the flame gun at full combustion was 6.1 kW. The distance between the gun nozzle and the polymer surface was fixed at 200 mm for all tests. The flame was scanned over the surface in a regular pattern as shown in Fig. 1. The scanning speed was set at 200 mm s^{-1} and the vertical step between each horizontal pass at 10 mm. A pass is defined as one traverse of the sheet width (L_x in Fig. 1) and one scan is one coverage of the entire face of the sheet (L_x by L_y in Fig. 1). It required 10 passes and 5 s to cover the face of the substrate from top to bottom and finish one scan. The infrared (IR) heater irradiated the entire surface are of the sheet and was fixed at a pre-selected power level for each trial. The effective power density on the surface was controlled at a series of fixed levels between 10 kW and 1 MW/m^2. The coating was irradiated immediately after deposition.

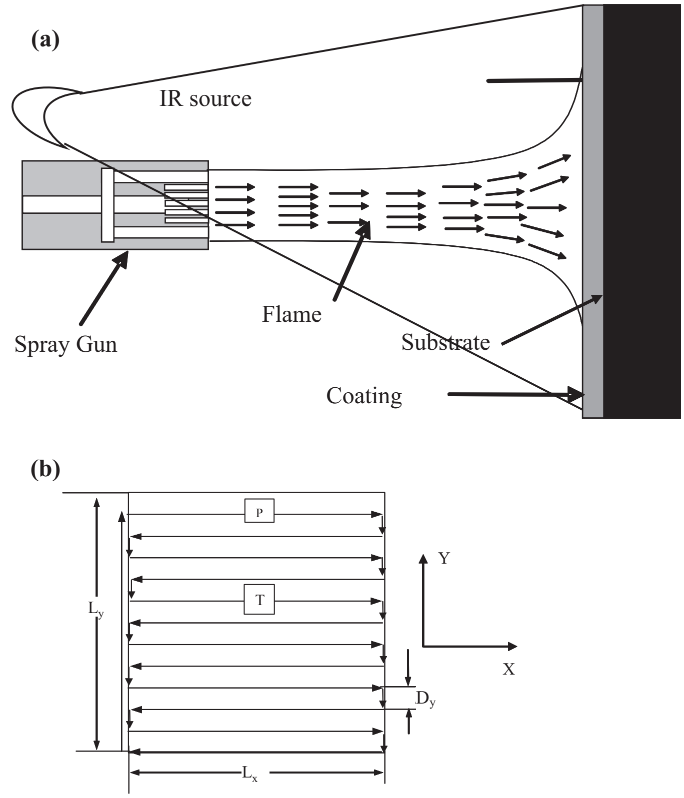

Fig. 1. Schematic of deposition and IR treatment: (a) process set up and (b) scanning process.

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 and flame temperature profiles could be obtained. The temperature profiles of the flame with and without the substrate were measured. In the former case, a square 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 models

3.1. Model for interaction between flame and coating

To simplify the computational model, the following assumptions were used:

i. The heat transfer in the coating and substrate is one-dimensional since the thickness is over two orders of magnitude less than its length and width.
ii. The thermal properties of the coating and substrate are constants, which do not change over the temperatures used.