



Process control for thermal-spray deposition of thermoset coatings using computer simulation



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ABSTRACT

Thermal spraying is a green solvent-free process with the potential of applying polymer coatings to large components in-house or on-site without the need for prolonged drying. Almost no systematic research has been undertaken on thermally spraying thermoset coatings owing to the complexity and difficulty of managing the curing process. An adequately cured thermoset coating could not be deposited by thermal spraying owing to insufficient cumulative time above the cure temperature. Preheating and post-heating the substrate under a constant heat source were not successful as they led to non-uniform curing, residual stress and the risk of overheating. This study develops and validates a computer model that simulates the deposition of thermoset coatings on metal substrates using thermal spraying and high-energy infrared irradiation. The model uses readily-available commercial software and enables precise control of the coating process to improve energy efficiency and coating quality. Further research showed that evenly cured coatings could be achieved by using variable heat fluxes and controlled utilization of inward conduction from the outer surface layers. Self curing during cooling was significant and may be employed to increase energy efficiency. The thickness of the metal substrate was shown to be an important variable as it acts as a heat sink and, for heavy sections, can substantially increase energy consumption. The results indicate a need for sufficiently accurate process control and provide a suitable methodology for the deposition of thermoset coatings.

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1. Introduction

Polymer coatings are applied to engineering components mainly by painting, electrostatic spraying or fluidized bed dipping. Although these processes have been successful over the years, there is no one individual process that has all of the following attributes: free from environmental emissions, enabling deposition on large components in-house or structures on-site, no need for prolonged drying and avoiding variable coating quality. Thermal-spray deposition has the potential to address these collective deficiencies.

Thermal spraying is a generic family of coating processes in which the coating material, usually in the form of a powder, is injected into a hot jet or flame, where it is melted, accelerated and projected onto a substrate to form a coating. Combustion flame spraying, plasma spraying and high-velocity oxy-fuel spraying are typical thermal-spray processes. The behaviour of metallic and

ceramic particles during thermal spraying is well documented but far less attention has been given to polymers.

The use of polymers in thermal spraying is gradually increasing but relates almost exclusively to thermoplastics and very little work has been undertaken on thermoset polymers. However, thermoset coatings provide a much superior performance to that of thermoplastics in terms of barrier properties, corrosion resistance, abrasion resistance and adhesion [1–4]. This is the underlying reason why over 95% of the powder coatings market consists of thermosets. The property level of thermoplastics could be raised by increasing their molecular weight but this inevitably raises their viscosity to the detriment of porosity and adhesion in the coatings. This deleterious rise in viscosity could, in turn, be overcome by increasing the processing temperatures but, in practice, it would be impracticable due to the risk of degradation and evolution of hazardous gases.

Despite its considerable potential, thermal spraying of polymer coatings remains a relatively minor activity. An important reason for this is that the process has only been successfully used for neat thermoplastics [5–12] e.g. polyamide, polyethylene, PMMA, vinyl chloride copolymers or thermoplastic composites [13–15].

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Although thermoset coatings are much more important economically than thermoplastic coatings, little work has been undertaken on their deposition by thermal spraying. This is largely because the formation of thermoset coatings is much more complex and demanding than that of thermoplastics. Thermoplastic deposition only requires the particles to melt in the flame without degradation [16], flow on impact with the substrate and then bond with the substrate and surrounding splats to form a continuous, aggregate coating.

Thermosets, however, have the additional requirement of cross-linking or curing and this further complexity is responsible for the lack of successful work undertaken on thermally sprayed thermoset coatings. As well as melting without degradation, thermoset particles must not crosslink in the flame, but must flow into splats, bond to form a coherent deposit and then cross-link to produce a fully cured coating (cross-linking in the flame greatly increases the viscosity of the particles and prevents adequate flow on the substrate). In electrostatic spraying, the control of crosslinking in an oven is relatively easy since the oven treatment is essentially isothermal and curing can be controlled by fixing both the temperature and time (most commercial powders in powder-coating processes are cured at 160 to 220 °C for 5 to 20 min). The thermal characteristics of flame spraying, on the other hand, are much more complex. The flame sweeps across and down the substrate surface depositing one or more layers until the required thickness of coating is built up. The hot gas jet from the spray gun impinges on and flows out laterally over the substrate or underlying layers of coating [17,18]. This imparts significant thermal energy into the coating, which can have a substantial effect on its properties, particularly for polymeric materials. Further research [19] showed that the temperature of a polymer coating during thermal spraying varies widely: for example, from 100 °C to 180 °C in just one sweep of the flame across the width of the substrate. This is expected to have a major influence on the curing of thermosets.

The thermal behaviour of a polymer is distinctly different from that of metals and ceramics because of its much lower melting and decomposition temperatures together with substantially lower thermal conductivities, wider liquid ranges and higher melting viscosities. The greater sensitivity of polymers to temperature compared with most metals and ceramics implies that the process window will need to be much narrower and, importantly, this will require more precise process control than that used in the spraying of metals and ceramics.

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 research on process control. For example, Xia et al. [20] have experimentally investigated the effect of processing parameters on the temperature profile in the coating and substrate during thermal spraying. This interaction was considered by the latter authors to be particularly important when temperature-sensitive materials, such as hydroxyapatites, were used as coating materials [21]. Sufficiently heating without overheating the surface is also likely to be a challenge for the thermal-spray deposition of thermosets [16]: the requirement is heating to a temperature that provides production-efficient crosslinking but avoids polymer degradation and the risk of the evolution of noxious gases. The very low thermal conductivity of polymers (e.g. $0.19 \text{ W m}^{-1} \text{ K}^{-1}$ for epoxy compared with $51.9 \text{ W m}^{-1} \text{ K}^{-1}$ for plain carbon steel) is likely to exert a major influence on heat flow away from the surface and its effect on overheating will be investigated in this paper.

The primary heat source in thermal spraying is the hot jet (combustion flame or plasma jet) into which the feedstock powder is injected. However, the temperature profile created on the surface of and within the depositing polymer coating is highly variable so that precise control is challenging. The use of high-energy infrared radi-

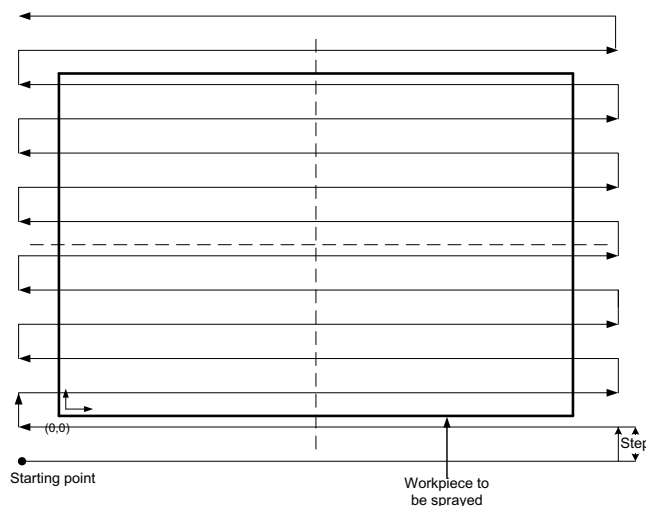


Fig. 1. Schematic of spray-torch movement over a rectangular substrate.

ation either during or after deposition has potential in this regard and will form part of this study.

Producing high-quality thermoset coatings needs close control of the temperature profile in the coating and the substrate. This requires knowledge of the interaction between the applied heat sources and the coating/substrate. Experimental work can be used to provide this knowledge but is time consuming and expensive. Computer simulation has the ability to generate detailed information which, in conjunction with limited experimental work, can develop a framework for process control much more efficiently. This paper will use well-known commercial software that is readily available for industrial users to determine the effect of critical process parameters on temperature profiles and curing.

2. Experimental details

The coating materials used for the thermal spray deposition trials in this study were epoxy (Interpon PZ) and polyester (Interpon D1063) powders supplied by Akzo Nobel (Gateshead, UK). Plain carbon steel plates of 150 mm × 100 mm with varying thickness were used as substrates. The materials properties and required curing schedule at 200 °C are given in Table I.

The coatings were deposited by combustion flame spraying with acetylene as a fuel gas, compressed air as a source of oxygen, cooling and carrier gases. The spray torch was mounted on a robotic traverse unit. Fig. 1 shows the movement of the torch to perform a complete scan of the substrate as needed during pre-heating, the coating deposition and post-deposition heating of the coating. The arrows represent the direction of movement of the torch and show the gaps and overlaps that ensure that the workpiece is fully coated. The second scan can be applied using the same route and so on for multi-scans. Control parameters include scanning speed, step distance and number of complete scans of the substrate.

The thermal history of the coating and substrate was measured in-situ using thermocouples and infrared pyrometers during the entire process including preheating, deposition and post-heating of the coatings. The information obtained is important for the control of the process parameters aimed at achieving sufficient crosslinking without degradation of thermosetting polymers. The coating surface temperature was monitored remotely using Raytek® IR thermometers. The coating-substrate interface temperature was measured using thermocouples (K type) with an 8 channels Pico® data TC-08 data loggers. Fig. 2 shows the positional coordinates of thermocouples on a 150 mm × 100 mm substrate under deposition.

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