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Residual stress development in cold sprayed Al, Cu and Ti coatings

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Abstract

Residual stresses play an important role in the formation and performance of thermal spray coatings. A curvature-based approach where the substrate–coating system deflection and temperature are monitored throughout the coating deposition process was used to determine residual stress formation during cold spray deposition of Al, Cu and Ti coatings. The effect of substrate material (carbon steel, stainless steel and aluminium) and substrate pre-treatment (normal grit blasting, grit blasting with the cold spray system and grinding for carbon steel substrate) were studied for all coating materials with optimized deposition parameters. Mainly compressive stresses were expected because of the nature of cold spraying, but also neutral as well as tensile stresses were formed for studied coatings. The magnitudes of the residual stresses were mainly dependent on the substrate/coating material combination, but the surface preparation was also found to have an effect on the final stress stage of the coating.

Keywords: Cold spraying; Residual stresses; Aluminium; Copper; Titanium

1. Introduction

In cold spraying, the feedstock material in powder form is injected into a heated gas jet behind the nozzle, from where it is propelled onto the substrate with compressed and heated gas, generally nitrogen or helium. Solid-state particles are accelerated in a high-pressure supersonic gas jet, causing the particles to plastically deform during the impact with the substrate or with the previously deposited coating itself. Above a certain particle velocity, which is characteristic of the respective coating material as well as e.g. the powder oxide scale thickness, particle size distribution and morphology, the particles can form a dense, solid, well-adhered coating upon impact. Because of lower operating temperatures compared with more conventional thermal spray methods, cold spraying is highly suitable for depositing oxygen and temperature sensitive materials such as aluminium, copper and titanium. Also, thick coatings can be produced without adhesion failure from several materials. The high kinetic energy/low temperature formation of the coating leads to a wrought-like microstructure with near theoretical density values [1–4]. The distinguishing feature of the cold spray process compared with conventional thermal spray processes is that the detrimental effects of high temperature oxidation, evaporation, melting, recrystallization, phase transformations, residual stresses, decohesion and other concerns associated with thermal spray methods can be minimized or even eliminated [5].

In conventional thermal spraying, like plasma spraying, most of the residual stresses originate from the quenching of the molten particles. The temperature drop in the solidification of molten particles upon impact with the substrate leads to tensile stresses (also known as quenching stress) because the contraction is restricted by the adherence to the substrate [6,7]. The temperature of the substrate is also typically increased during deposition of the coating. When the substrate–coating system is cooled down to e.g. room temperature after the deposition, a thermal mismatch stress (also known as thermal stress) is generated. The nature of

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the thermal stress (tensile, neutral or compressive) is determined by the difference in the coefficients of thermal expansion (ΔCTE) of the coating and the substrate [7,8]. In high-velocity thermal spray systems, like high-velocity oxy–fuel (HVOF) or high-velocity air–fuel, and cold spraying, a compressive component (also known as peening stress) can be introduced during the deposition. This is caused by the high-velocity impact of the particles causing plastic deformation of the substrate and/or previously deposited coating material [9]. Typically, all of these components will be present in thermal sprayed coatings, but the magnitude of the quenching, thermal and peening stress is dependent on, for example, the temperature difference before and after the impact of the particle with the substrate, the temperature difference of the substrate–coating system during and after the spraying, and the ability of the substrate and coating to plastically deform and work harden upon impact of the particle. The combined effect of quenching and peening is known as evolving stress, and represents a stress developed when a layer of material is deposited in the substrate–coating system. Compressive evolving stress indicates that the peening effect is more dominant, and the tensile mode indicates that the quenching effect is more dominant [10,11].

In the cold spray process, the feedstock powder, usually with metal as a main component, is injected into a gas stream and accelerated to a speed of ~500–1000 m s^{-1}. When the particles impact on a metallic substrate, the plastic deformation of the particles under pressure generates new interfaces with conformal contact, enabling metallic bonding, which forms the coating. Although a localized increase in temperature occurs at the interface due to the impact, the overall temperature of the substrate does not increase considerably. The bond strength and cohesion of the coating are determined in part by the residual stresses arising from the peening process [12]. Residual stresses are very important factors influencing the make-up of the coating–substrate system, as well as its performance. In cold spray coatings, a compressive residual stress in the coating can be expected as a result of the plastic deformation, in a similar fashion to some HVOF coatings [13].

In situ residual stress measurements have been reported in the literature for plasma- and HVOF-sprayed coatings [10,11,13]. The same curvature-based method has also been used to extract the in-plane elastic modulus or the CTE of the coatings deposited. Elastic modulus of the coatings can be calculated from the coating–substrate system curvature change due to the thermal mismatch [10,11]. Sprayed beams can be subjected to low temperature thermal cycling after deposition. In these experiments, the deposited coating–substrate system is uniformly heated (e.g. to 150 °C) and cooled down to room temperature by free convection. The cooling portion can be taken for analysis. According to Tsui and Clyne's [14] curvature change model, during cooling, the elastic modulus can be calculated from Eq. (1):

$$\Delta k = \frac{1}{\Delta R} = \frac{6E'_c E'_s t_c t_s (t_c + t_s)\Delta T \Delta\alpha}{E_c^2 t_c^4 + 4E_c E_s t_c^3 t_s + 6E_c E_s t_c^2 t_s^2 + 4E_c E_s t_c t_s^3 + E_s^2 t_s^4} \tag{1}$$

where Δk is the curvature change due to the decrease in temperature (ΔT) and $\Delta\alpha$ is the ΔCTE between the deposit and the substrate. t_c is the coating thickness, t_S is the substrate thickness, and E'_c and E'_S are the moduli of the coating and the substrate, respectively. Continuous monitoring of the curvature and the temperature during the heating–cooling experiment allows the estimation of the deposit modulus by the curve-fitting method. By spraying coatings with the same parameters on substrates having different CTEs, the CTE of the coating can be determined by iterating the unknown E_c and α_c, Young's modulus and CTE of the coating, respectively. However, the different substrate materials might have a minor effect on the coating structure and, because E_c is known to be more sensitive than α_c to the substrate material, an alternative method to determine the E_c could be used.

Several methods have been used for residual stress measurement and estimation of cold sprayed coatings. Methods including theoretical models and experimental methods like the modified layer removal technique, X-ray and neutron diffraction [15–19] have been used for residual stress characterization of cold spray coatings, but no information about the in situ measurements have been reported in the literature. In this study, for the first time, an in situ technique has been used to measure the in situ residual stress of several cold spray materials.

2. Experimental procedure

2.1. Materials

Three different powders, three different substrate materials and three different substrate pre-treatments were used in this study.

The Al, Cu and Ti powders are commercially available and especially designed for thermal spraying. The Al powder was provided by TLS Technik GmbH, the Cu powder was from H.C. Starck (Amperit 190.068) and the Ti powder was from Gfe GmbH. Gas atomized aluminium powder had a purity of 99.7% (according to manufacturer). The particle size distribution was $-50 + 10$ μm with an average particle size (d_{50}) of 32 μm. The copper powder was also gas atomized with 99.89% purity (according to manufacturer), a particle size distribution of $-35 + 10$ μm and average particle size of 22 μm. In the case of titanium, a crushed powder with purity of 99.7% (according to manufacturer) was used to deposit the coatings. The particle size distribution was $-80 + 20$ μm with an average particle size of 38 μm.

Coatings were deposited on carbon steel (S355), stainless steel (AISI316) and aluminium (6061-T6) substrates with dimensions of 228.6 mm × 25.4 mm × 2.5 mm. Three