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Effect of higher deposition temperatures on the microstructure and mechanical properties of Al 2024 cold sprayed coatings

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ABSTRACT

Cold spray is a coating technology that works at temperatures below the melting point of the initial powder and appears to be an interesting alternative to repair aeronautical components. This work evaluates the effect of temperature on the quality and properties of the aluminum alloy 2024 coatings deposited by cold spray. The coatings were sprayed at a conventional temperature of 350 °C and at a non-conventional one of 500 °C on aluminum 2024 T351 substrates. Electron microscopy was used to analyze the microstructure. Depth sensing indentation and Vickers microhardness tests were conducted to determine the elastic modulus and hardness. Both coatings exhibited a work hardened microstructure, and no modifications in phase composition were observed. However, the coating processed at 500 °C presented hardness values lower than those obtained for the coating processed under conventional conditions. The hardness of the coatings increased regarding to the initial powder particles due to the plastic deformation induced during spraying. Comparing both coatings, the study indicates that cold spray at 500 °C could be adequate for maintaining and overhauling aluminum components used in the aeronautical industry.

1. Introduction

Aluminum alloy 2024 (Al 2024) is extensively used in aeronautical components in which high strength and light weight are necessary [1,2]. Traditionally, these components are replaced when their reliability is compromised due to wear or damage, which increases maintenance costs. Therefore, the development of reliable reparation techniques for the aeronautical industry is especially important. Nowadays, coating deposition methods are being studied as a less expensive and more environmentally friendly alternative of maintenance so the local damage is repaired without replacing the entire component [3,4].

Welding and thermal spray techniques have already been used for maintenance operations but have certain associated limitations. Most of these methods work at high temperatures (over the melting point of the initial feedstock powder). These deposition temperatures can favor the development of tensile residual stresses and oxidation during the coating generation, thereby promoting a reduction in their fatigue performance by cracks propagation and the appearance of undesirable phases [5]. However, cold gas dynamic spray (CGDS), or simply cold spray (CS), is a coating technology that works at temperatures below the melting point of the initial powder and appears to be an interesting option to repair these aeronautical components while avoiding the detrimental effects of high temperature [6–8].

The bonding effect facilitated by the high temperatures reached in high temperature thermal spray techniques, such as Plasma Spray or High Velocity Oxi-Fuel, is replaced in CS by the increase in the particle deposition velocity. The particles are accelerated using a preheated compressed gas (air, nitrogen, helium or a mixture therein). This particle and gas flow is conducted through a de Laval nozzle to enhance the velocity. The high impact velocities of the particles (between 200 and 1200 m/s) on the substrate enable the coating development because of the plastic deformation of the particles [6]. Thus, powder particles become embedded and generate coatings by the stacking of the sprayed material. The lower temperatures provide coatings with a reduced oxidation, lower tensile residual stresses and avoid the formation of undesirable phases, maintaining the initial composition of the powder [6,8]. Therefore, the development of thick coatings is permitted, which is promising for repairing purposes.

The process gas type, temperature, pressure and stand of distance (SOD) along with the nozzle are the primary manufacturing parameters

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Table 1
Size and chemical composition data of the Al 2024 powder provided by the manufacturer.

Al 2024 powder									
Size (μm)	20–63								
Element composition	Al	Cu	Mg	Si	Fe	Mn	Cr	Zn	Ti
wt. (%)	Balance	3.8–4.9	1.2–1.8	0.5	0.5	0.3–0.9	0.1	0.25	0.15

that control the quality of the CS coatings. The appropriate values of these parameters are unique for each sprayed material. Thus, coating optimization for a more efficient deposition and better coating performance is primarily focused on the choice of the adequate deposition parameters. Other factors, such as the morphology or size of the sprayed particles or surface pretreatments of the substrate, also influence the coating performance [6,8,9].

In recent years, coatings of aluminum (Al) alloys sprayed by CS have been investigated using different deposition parameters to develop well-bonded coatings with low porosity [10–18]. A range of process gas temperatures between 200 °C and 450 °C have been previously used to deposit this material. Ziemain et al. [12] studied the effect of substrate surface roughening and CS coating on the fatigue life of AA2024 specimens. The coating was generated by powder particles accelerated with a nitrogen carrier gas at a temperature of 230 °C and 3.45 MPa pressure. Rokni et al. [19] deposited nanocrystalline 5083 Al powder via helium as the process gas. In this study, the pressure and temperature of helium were maintained at 20 bar and 450 °C at the heater exit, respectively. This high temperature was used in order to decrease the critical impact velocity needed to deposit this nanocrystalline powder. Nevertheless, to the best of the authors' knowledge, there are no studies examining the use of higher deposition temperatures for Al alloys. The application of higher deposition temperatures is interesting because the thermal softening of the particles has been reported to facilitate the bonding process to increase the deposition efficiency [8,20–22]. The bonding of the coatings in CS is based on the deformation of the particles that could be enhanced by the thermal softening.

T. Stoltenhoff et al. [20] developed models of the gas and particle flow fields for the CS process. This study determines the increase in the particle velocity (v_p), temperature (T_p), and deposition efficiency (DE) with the increase in the deposition temperature using fluid dynamic calculations. For example, increments of 30 m/s for v_p and 50 °C for T_p, lead to a 25% increment on DE for copper CS coatings sprayed under certain conditions. T. Schmidt et al. reported experimental work [21], based on the previous quoted models [20], that also demonstrates the improvements in strength and electrical conductivity for copper CS coatings when spraying at higher temperatures. In addition, G. Bae et al. [22] confirmed the enhancement of the adhesive and cohesive bonding on Ni CS coatings when the Ni particles are thermally softened, verifying their previous results of a finite element model.

Therefore, the aim of this work is to study the effects of increasing the spraying temperature on the quality of Al 2024 coatings deposited by CS on substrates of the same alloy. For this purpose, the microstructure and mechanical performance have been investigated on Al 2024 coatings sprayed at a conventional temperature of 350 °C and at a non-conventional temperature of 500 °C. The microstructure was analyzed using scanning and transmission electron microscopy to evaluate the differences in the deposition created by increasing the gas process temperature. Conversely, the mechanical performance was evaluated by depth sensing indentation and Vickers microhardness tests to study the evolution of the elastic modulus (E) and hardness (H) with the gas process temperature. Both the microstructure and mechanical properties obtained from the coatings have been compared to those obtained from a substrate of Al 2024 T351, the material used in aeronautical components. The primary goal of this work is to evaluate the effects of temperature on the viability of CS for the maintenance and overhaul of aeronautical components by comparing the CS coating performance to that observed in the substrate.

2. Materials processing

2.1. Raw materials

Al 2024 coatings were deposited onto Al 2024 substrates with the aim of studying the application of coatings deposited by CS for repairing Al components. Commercially available gas-atomized Al 2024 powder (TLS Technik GmbH, KG, D-06733 Bitterfeld, Germany) was used for the deposition. The composition of the particles reported by the supplier is shown in Table 1. The particles were characterized by spherical geometry (Fig. 1a) with a size distribution mainly ranged between 20 and 63 μm (Table 1). The substrates were supplied by AVIO AERO (GE Aviation) with aeronautical grade and in T351 temper. The surface coated by CS was 50 mm × 50 mm and the thickness was 4 mm. The standard surface preparation, consisting of a grit blasting process, was carried on the substrates [23]. The average roughness of their surfaces, Ra, was 17.17 ± 1.88 μm measured by a profilometer (Surftest SJ-301, Mitutoyo, Japan).

2.2. CS deposition

The depositions were performed with a CS system Kinetiks 4000 (CGT Cold Gas Technology, Ampfing, Germany) using nitrogen as the process gas. A Polybenzimidazole (PBI) polymeric nozzle designed for Al powder spraying was used at 350 °C at a pressure of 3.75 MPa, as mainly used up today for the Al alloy deposition [15]. The process gas temperature is limited by the polymeric nature of the nozzle material. To surpass this limitation, a silicon carbide nozzle, developed by Impact Innovations GmbH (Haun/Rattenkirchen, Germany) equipped with a customized water cooling system (Impact Innovations) was installed on the CS Kinetiks 4000 and used at the higher process gas temperature. This second configuration of CS with the SiC nozzle and water cooling was tested up to 650 °C while preserving the same feedstock material, confirming the suitability of the equipment configuration, even if the process stability progressively decreases as a function of process gas temperature due to the progressive clogging of the nozzle. The two major contributions causing nozzle clogging are the characteristics of the feedstock material in terms of such parameters as composition, melting temperature, and particle size and shape, as well as the process gas temperature. The higher process gas temperature increases the particle adhesion to the walls of the nozzle, particularly near the throat both at the converging and diverging parts where the intensity of particle-wall collisions is relevant. Thus, the operating temperature was selected as 500 °C to balance the desired enhanced particle softening and the process stability to ensure a reliable and repeatable deposition process. At this temperature, the capability to have a stable process for up to 1 h of consecutive spraying is reported, which is sufficient to complete a typical repair of aeronautical applications. A second parameter that was tuned for optimization was the nozzle traverse speed, which has been experimentally tuned in order to preserve substrate temperature lower than 150 °C. At the lower temperature, 50 mm/s traverse speed was used. At the higher temperature, a traverse speed of 100 mm/s was set to mitigate the thermal input to the substrate induced by the hot process gas flow, which is detrimental to the base material