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Characterization and modeling of the bonding process in cold spray additive manufacturing

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Abstract

Additive manufacturing (AM) processes are used to build structural components layer-by-layer. Cold spray is considered an AM process, whereby particles impact a substrate at high velocities to generate the deposition layer. Effect of spray angles on bonding strength at the cold spray deposit and substrate interface was experimentally investigated. The results showed that bonding strength increased with decreasing spray angle from the normal direction (90° spray angle), and the maximum bonding strength was observed at 45° spray angle; however, the deposition efficiency and strength of the bulk deposit material decreased with decreasing spray angle. 3D finite element modeling of single-particle impact combined with experimental observation of "splat" deposits was conducted to understand bonding process under different spray angles. Good correlation between numerical and experimental results was achieved. The relationships between parameters contributing bonding formations (e.g., plastic deformation and temperature rise due to impact) and processing parameters (e.g., spray angles, impact velocity, pre-heating temperature) were established and discussed. These relationships are useful for understanding bonding mechanisms and strengths of deposits sprayed at different angles and can be used to define an optimized spray angle. The modeling results also revealed that increasing particle impact velocity and pre-heating temperature promoted deposit quality, but in different respects. Finally, the influence of different primary accelerating gases (helium vs nitrogen) on the material properties of the deposits was investigated. The tensile testing showed that fully dense deposits produced with different gases had similar stiffness and yield strength, but different ductility. The particle impact model was further used to explain the different material behaviors, which also demonstrated feasibility to connect the spray parameters and the material properties via modeling for optimizing cold spray process.

Keywords: Additive Manufacturing; Cold spray; Particle impact; Modeling; Bonding mechanism

1. Introduction

The cold spray process is a high-rate powder deposition additive manufacturing (AM) technique. It can be used for creating new parts, repairing structures, or applying a coating to a surface or part. To deposit a layer of material, the feedstock powder particles are accelerated in a supersonic jet of compressed cold or pre-heated gas to high velocities and then directed toward a substrate. Upon impact, the powders deform plastically and bond to the surface. The supersonic gas jet is produced using a converging-diverging de Laval nozzle [1]. The expansion of the gas in the divergent section of the nozzle will reduce the gas temperature, resulting in a process whereby the particles remain in a solid state prior to impacting the substrate, thus reducing oxidation of the deposited layer and percentage of volumetric porosity [2,3]. Unlike alternative AM techniques and thermal spray processes, cold spray deposition will retain the chemistry, phase composition, and grain structure of the solid state precursor powder material.

Experimental observations indicate that particle bonding with the substrate occurs only when the particle velocity exceeds a critical value, termed "critical velocity." The critical velocity has been identified for several materials in different open literature [4–7] and is perceived to be a function of material properties, particle size, initial impact temperature, and melting temperature [6,7]. For most of the materials deposited by cold

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spray to-date, the critical velocity is in the range of 150–900 m/s [8].

A number of works have been carried out in the past decade to explain bonding mechanisms in the cold spray process, including metal jet formation caused by plastic flow coupled with subsequent removal a surface oxide layer [9,10], adiabatic shear instability at the interface during impact [5,6,10–15], development of interfacial instability which results in the formation of interfacial roll-ups and vortices leading to micro-scale mixing of the material [5], mechanical interlocking of substrate material into the deposited layer due to the topology of the crater [5,8], and/or, for some material systems, melting at the interface during impact which may influence the bonding process [16]. Metal jet formation due to severe plastic deformation leads to the removal of the surface oxide layer, allowing true metal-to-metal contact to be established. Hussain et al. [8] used transmission electron microscopy (TEM) to examine the oxide layer between individual particles and its effect on bond formation and found evidence of ruptured oxide film in the deposited layers. Finite element modeling work by Assadi et al. [6] showed inhomogeneous temperature and strain distributions at the impact interface, suggesting that the bonding is confined to only a fraction of the interacting surfaces because of the incomplete removal of the oxide layers between contacting surfaces [17]. The adiabatic shear instability, where plasticity-induced thermal softening overcomes the strain hardening, occurs as a result of high strain rate deformation processes and creates a metal jet consisting of the particle and substrate material. Adiabatic finite element analysis of single particle impact based on an axisymmetric modeling configuration has been performed by different researchers to study adiabatic shear instability for either a similar or dissimilar material bonding process [5,6,10–15]. Grujicic et al. [5] also proposed that bonding could occur due to the development of interfacial instability which results in the formation of interfacial roll-ups and vortices leading to micro-scale mixing of the materials at the interface. They believed that the material at the contact interface behaved like a viscous fluid under impact conditions due to extremely high pressure and material flow. The bonding mechanism was also proposed to be a result of mechanical interlocking of substrate material into the deposited layer due to the topology of the crater [5,8]. Hussain et al. [8] stated that in most cases, mechanical interlocking is able to account for a large proportion of the total bond strength. In addition, the increase in substrate and particle temperature at the jetting area indicates that melting may occur at the interface and influence the bonding process [16]. This type of metallurgical bonding only contributes significantly when the substrate had been polished and annealed prior to spraying [8]. Mechanical interlocking and metallurgical bonding are commonly perceived to be two dominant mechanisms of metallic bonding in the cold spray process.

The interparticle bond formation of the deposit build-up can be considered in similar terms to that for the particle/substrate interactions. Deposition performance of particles in the cold spray process is influenced by many factors, such as particle impact velocity and pre-heating temperature, spray angles, material properties, particle size and morphology, surface treatments, etc. Many works in the past studied the influence of particle velocity or temperature on bonding based on an axisymmetric, single-particle impact model. Some works [18,19] reported the effect of spray angles on cold spray deposition and the relation between the spray angle and relative deposition efficiency. Although there exist some meaningfully findings, the effect of spray angles on the bonding process is still not well understood and the relation between bonding strength at cold spray deposit and substrate interfaces, deposition efficiency, and strength of bulk deposit material sprayed at different angles was not revealed yet. In addition, development of a modeling framework is required to correlate the process parameters to bulk cold spray material behaviors.

Therefore, the objective of this paper is to investigate the effect of spray angles on bonding strength and its relation with deposition efficiency and strength of produced deposit materials, as well as the effect of primary accelerating gases on cold spray material behavior. Experimental investigation was done to study effect of spray angles on bonding strength at the deposit and substrate interface. The results also revealed the relation between deposition efficiency and strength of bulk deposits sprayed at different spray angles. 3D finite element modeling of single-particle impact, combined with experimental observation of "splat" deposits, was also systematically conducted. Good correlations between experimental and numerical results were achieved. Based on both results, the relationships between representative parameters contributing bonding formations (e.g., plastic deformation and temperature rise due to impact) and processing parameters (e.g., spray angles, impact velocity, pre-heating temperature) were established for better understanding of bonding mechanisms and strengths of deposits sprayed at different angles. Substrate preheating was reported to play an important role for the formation of the first layer deposit [20,21]. However, the present work was focused on study of the thermally-softened powder deposition on room temperature surfaces. Furthermore, the influence of different primary accelerating gases (helium vs nitrogen) on the deposit properties was also investigated. Tensile testing was conducted to characterize material properties of the cold spray deposits. The single particle impact model was used to explain different material behaviors observed experimentally, which also demonstrated feasibility to connect the spray parameters and the material properties via modeling for optimizing cold spray process.

2. Experimental procedure

2.1. Materials

In the present work, the commercial gas-atomized aluminum 6061 powder provided by Valimet, Inc. (Stockton, CA) was used to produce the cold spray deposit. Fig. 1 shows the spherical morphology of the powder, and Fig. 2 shows the particle size distribution measured with a Microtrac S3500. Most particles are in the size range of 20–70 μm. The mean particle diameter is 40 μm. The substrate material was aluminum 6061-T6 (Al6061-T6) alloy, cut from extruded stock material. Prior to spraying, the powder was heat treated to the T6 condition to match that of the substrate. This is atypical for cold spray processing of 6061