Novel Cold Spray Nanostructured Aluminum

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Abstract

This paper discusses the introduction of a relatively new materials consolidation process, referred to as 'Cold Spray', which has been shown to meet the low-temperature, high velocity criteria for the production of dense, oxide-free metal-base nanostructured materials that may contribute to stronger near net-shape spray nanostructured components and as an enabling repair technology.

When spraying nanostructured coatings, there are particular requirements in preserving the microstructure and functionality of the feedstock powder in the final bulk material. This is especially true when depositing temperature sensitive and readily oxidizing materials such as carbides, nitrides, and nanostructered metals. For these materials, the goal is to replace most, if not all, of the thermal energy (i.e., flame temperature) with kinetic energy (i.e., particle velocity) so as to retain the nanostructure without contributing to coating oxidation or porosity. Osmotic consolidation, pressure filtration, and tape casting have been used to produce consolidated nanostructured materials with limited thickness.

The low temperature and high kinetic energy associated with the cold spray process allow for the retention of fine/nano grain structure, absence of phase change, capability for thick deposits, and promotion of compressive residual coating stress. These capabilities make the cold spray process an ideal approach to depositing nanostructured metal-base coatings, as well as nanostructured bulk materials. This paper will present data associated with the cold spray development and materials characterization of nanostructured 5083 aluminum.

Introduction

One concept to advance to ultra-high strengths in aluminum alloys is to consolidate parts using a nanograined powder source. Cold spray will not lead to thermal grain growth, if successful this will develop a new way for process bulk nanograined near net shaped parts. The consolidation of such powder has been achieved with promising success, however further powder development is require to enable bulk parts production.

Cold spray is a materials deposition process whereby combinations of metallic and non-metallic particles are consolidated to form a coating or freestanding structure by means of ballistic impingement upon a suitable substrate [1, 2, 3]. The particles utilized are in the form of commercially available powders, typically ranging in size from 5 to 100 µm, that are accelerated from 300 to 1,500 m/sec by injection into a high-velocity stream of gas. The high velocity gas stream is generated via the expansion of a pressurized, preheated, gas through a converging-diverging de Laval rocket nozzle. The pressurized gas is expanded to supersonic velocity, with an accompanying decrease in pressure and temperature [4, 5, 6]. The particles, initially carried by a separate gas stream, are injected into the nozzle either prior to the throat of the nozzle or downstream of the throat. The particles are subsequently accelerated by the main nozzle gas flow and are impacted onto a substrate after exiting the nozzle (Figure. 1). Upon impact, the solid particles deform and create a bond with the substrate [7, 8]. As the process continues, particles continue to impact the substrate and form bonds with the consolidated material resulting in a uniform deposit with very little porosity and high bond strength. The term "cold spray" has been used to describe this process due to the relatively low temperatures (-250 to --100 °C) of the expanded gas stream that exits the nozzle. This is illustrated in Fig X, which uses a cold spray model developed by Helfritch *et.al.*[12] to calculate the temperature of the gas as it expands from the nozzle as a function of inlet temperature and pressure.

The temperature of the gas stream is always below the melting point of the particulate material during cold spray, and the resultant consolidated material is formed in the solid state. Since the adhesion of the powder to the substrate, as well as the cohesion of the deposited material, is accomplished in the solid state at low temperatures, the characteristics of the cold spray material are quite unique in many regards. The low temperatures associated with the cold spray process are desirable when nanostructured powders are used as feedstock because the risk of grain growth and phase transformation is minimal or nonexistent. In addition, particle oxidation is avoided, as well as deleterious tensile stresses that occur during thermal contraction. Therefore, cold spray has the potential to produce nanostructured coatings with a bond strength superior to that of the substrate. With further advancement of techniques to manufacture 'cold spray' powders, greater cohesive strength should be possible when compared to conventional thermal spray and powder metallurgy processes.

The Young's moduli of cold sprayed deposits have been reported to be greater than 80% of bulk values [9]. The Army Research Lab (ARL) has developed a cold spray process for depositing 6061 aluminum that has achieved an ultimate tensile strength, yield point and Young's modulus greater than what has been reported in literature for wrought in the hardened 6061-T6 condition, which is solutionized, quenched and tempered, while the properties of the cold spray coating were taken in the as-sprayed condition. These characteristics are achieved because cold particles are less susceptible to oxidation, and high velocity impact creates dense, well consolidated material. The superior qualities of cold sprayed materials are required by certain applications. For example, the high heat transfer coefficient and electrical conductivity of cold spray materials favor their use in electronic applications [10]. Good corrosion protection is also achieved by dense, impermeable, cold sprayed coatings.

The deposition thickness produced by a single pass of the cold spray nozzle can vary from 0.01 to 1.0 mm, depending on the powder feed rate, nozzle traverse speed, and deposition efficiency. Multiple

coating layers can result in deposits several centimeters thick and some materials appear to have no limitation in the thickness that can be achieved. The width of a single pass of a conventional nozzle is approximately 5 mm, and large surfaces can be coated through multiple, slightly overlapping, parallel sweeps. Nitrogen can be used as the accelerating gas to produce a fully dense copper deposit, with several passes resulting in a coating that was approximately 2 mm thick. The individual copper particles consolidate into a dense, uniform deposit, which adheres tightly to the aluminum substrate. The copper is actually mechanically mixed with the aluminum at the interface. The microstructure resulting from the interaction of impacting particles and the substrate is analogous to materials that have been explosively bonded.

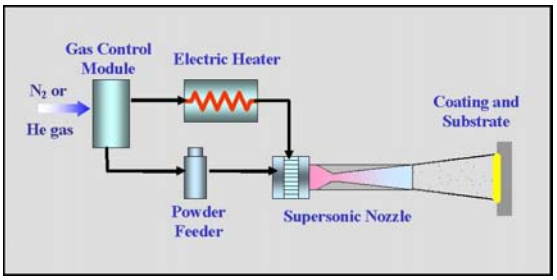

Figure 1: Cold spray system schematic

Experimental Procedure

Predictive models developed by ARL can be used to determine the impact velocity of accelerating particles as well as the 'critical' impact velocity. The critical impact velocity can be defined, as that which results in adequate consolidation of the particles. The exact amount of plastic deformation that each particle must undergo to result in an adequate consolidated deposit is still very much under debate, but as Figure 2 indicates, the critical impact velocity is approximately 650 m/s. Incorporating the cold spray process parameters used in this study with the accelerating gas set at a temperature of 400 °C and a main gas pressure of 400 psi, a 20 µm particle would achieve an impact velocity of 1438 m/s with helium and 697 m/s in a nitrogen gas stream, (Figure 3). The average particle size for the AA5083 was 56.7 µm, as the data presented in the particle analysis shows (Figure 4). However, this analysis also shows a larger percentage of particles that are > 100 µm. The corresponding impact velocity for the average particle size was approximately 850 m/s, as calculated for the accelerating gas set at a temperature of 400 °C and a main gas pressure of 400 psi. However, the impact velocity of some of the larger agglomerates (> 120 µm) cannot be achieved using the process parameters described.

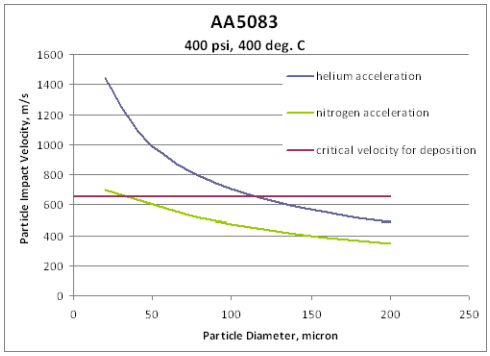

Figure 2:Critical impact velocity calculated with the helium accelerating gas set at a temperature of 400°C and with a main gas pressure of 400 psi.

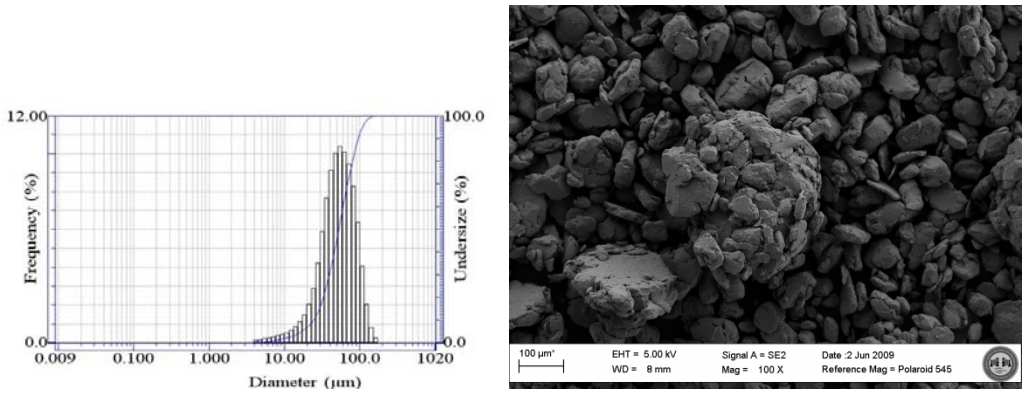

Figure 3 Particle size distribution of AA5083 powder (left). The mean particle size was 56.7 µm. Images of nano structured 5083 aluminum powder (right)

Results and discussion

The best operating process parameters were selected based upon several primary factors, including maximum temperature, deposition efficiency, density and nozzle clogging. Helium was used as the accelerating gas at a temperature of approximately 400 °C with a pressure of 400 psi. Figure 5 shows an as-polished cross section of the resultant deposit. Note the 'splat' or particle boundaries and the complete consolidation that was achieved using these process parameters. There were random voids observed within the structure that were later attributed to large agglomerates found in the original feed stock powder (Figure 8). These agglomerates were in excess of 100 µm and as such would not completely deform during impact, leaving behind these occasional defects. An attempt was made to sieve the feed stock powder using a 325 mesh sieve, which would remove any particle having a diameter greater than approximately 44 µm. The particle size analysis of the sieved powder shows new mean particle size of 33.9 µm with no particles larger than 65 µm (Figure 9) Additional spray trials were conducted and results indicated the elimination of these voids in the structure of the AA5083 cold spray deposit (Figure 10).

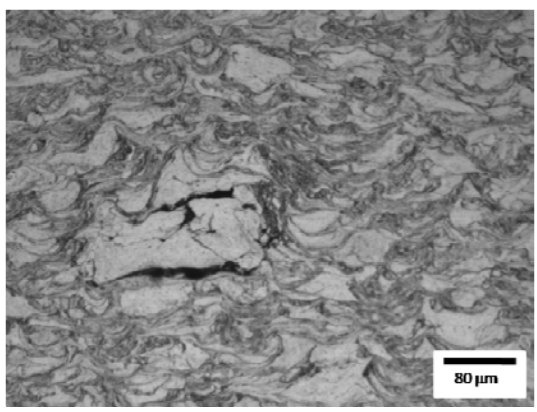

Figure 4: Optical microscope view of cold spray deposit of nanostructured AA5083. Note voids located near large undefromed particles.

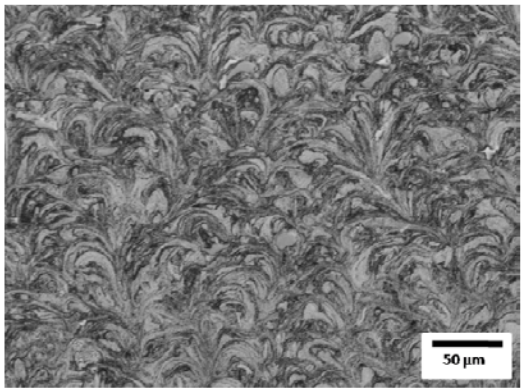

Figure 5: Optical microscope view of cold spray deposit of sieved nanostructured AA5083.

A typical bright-field TEM micrograph from cold-sprayed AA5083 is presented in Figure 6. Very little porosity and oxide inclusion were observed. Deformation of fcc-Al from high particle velocity deposition resulted in elongated grains with aspect ratio ranging from 2~3 to 1. Mean grain size was approximated at 100 ± 35 nm. Between nano-grains, excellent chemical bonding without deleterious voids or inclusions was observed as demonstrated by the high resolution TEM micrograph. However, inclusions and voids were occasionally observed at splat (e.g., prior particle) boundaries as presented in Figure. At the interface between AA5083 cold-sprayed coating and AA6061 substrate, excellent bonding was observed as presented in Figure 7 Certainly, inclusions of oxides were observed but not as continuous layer since they were broken apart due to the deformation of impinging particle associated with high velocity impact. Thus, a majority of the coating/substrate interface consisted of fcc-Al bonding between AA5083 and AA6061. Figure 8 presents X-ray diffraction patterns from cold-sprayed AA5083 and annealed AA6061 (e.g., uncoated bottom surface). While both patterns correspond to fcc-Al (i.e., also confirmed by electron diffraction from TEM), a noticeable compressive strain, estimated at 0.31% was observed for the cold-sprayed AA5083 coating.

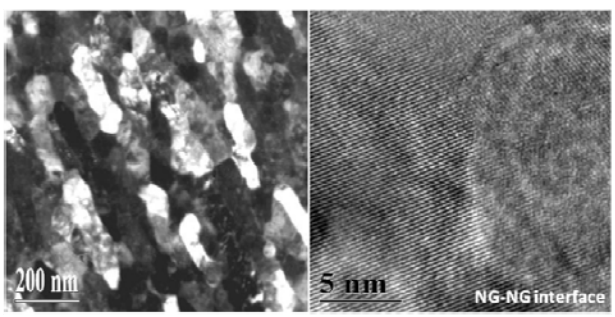

Fig. 6.0 TEM images of deposited AA5083 powder showing mean grain size of 100 ± 35 nm (left) and a grain boundary (right).

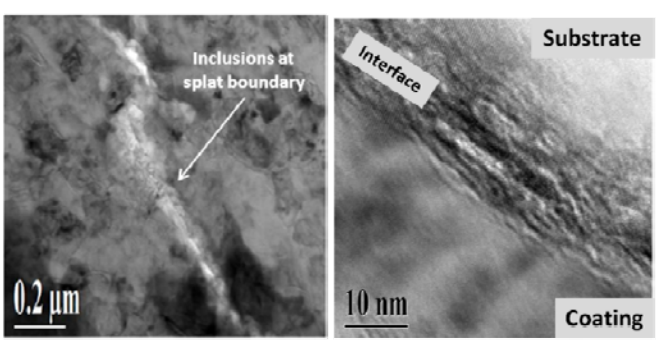

Fig. 7.0 TEM images of grain boundary inclusions (left) and the coating/substrate interface (right).

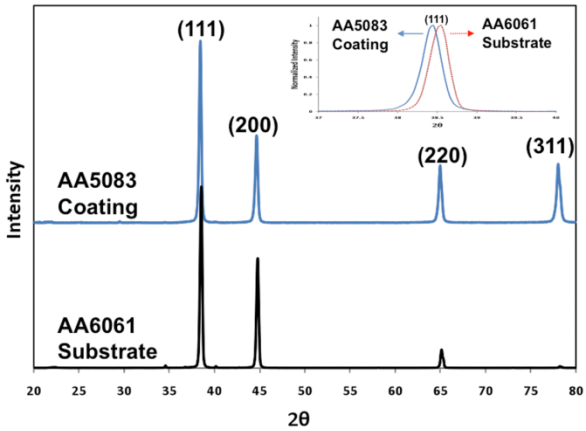

Figure 8: X-ray diffraction patterns from cold-sprayed AA5083 and uncoated bottom surface of AA6061 substrate

Conclusions

The cold spray process was used to consolidate non-cryogenically milled (NCM) AA5083 powder. Very little porosity and oxide inclusion were observed. Deformation of fcc-Al from high particle velocity deposition resulted in elongated grains with aspect ratio ranging from 2~3 to 1. Mean grain size was approximated at 100 ± 35nm. Between nano-grains, excellent chemical bonding without deleterious voids or inclusions was observed as demonstrated by the high resolution TEM microscopy.

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