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Process parameter optimization and characterization of cold spray pure and blended AA6061 powder depositions

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Abstract: Cold spray is a solid-state deposition method belonging in the thermal spray group of technologies that creates coatings, mass restorations, and additively manufactured components by accelerating feedstock powders at supersonic speeds via a de Laval nozzle. Once accelerated particles collide with a substrate or existing layer build up, severe plastic deformation from impact creates mechanical and metallurgical bonding. Among the many materials compatible with cold spray, aluminum 6061 alloy is a widely used, a general-purpose metal commonly found in industries such as automotive and aerospace as a structural material. Typically, metallic powders are manufactured with gas atomization and available as pure AA6061, or as a blend with various ceramics to obtain desired deposition mechanical, material, and manufacturing requirements. Additionally, a solid-state powder manufacturing method using mechanical grinding has emerged providing cold spray users with AA6061 powders of different morphology and metallurgy more like AA6061 bulk material. This study investigates deposition properties for pure gas atomized and ground AA6061 powders, and gas atomized powders blended with Al_2O_3, SiO_2, and ZrO_2. Cold spray depositions are characterized by studying their deposition efficiency, thickness, density, and microhardness. Effects of powder size distribution, morphology, and blending are correlated with deposition characteristics. Observations made include higher deposition efficiency and thickness with blended powders, and general hardness and deposition efficiency tradeoff for gas atomized powders, and high deposition efficiency and hardness for ground powder. Response Surface Methodology is used to determine optimum temperature and pressure conditions for powders, with deposition efficiency, thickness, and microhardness explanatory variables.

Keywords: Cold Spray, Powder Characterization, Process Parameter Optimization, AA6061

1. Introduction

Applications of the cold spray technology include component repair, coating, feature additions, and additive manufacturing all of which require deposition characterization to achieve economical and functional requirements. AA6061 aluminum alloy is an economical and widely available structural metal commonly found in automotive, aerospace, and in general structural applications with commercially available pure and ceramic blended feedstock powders. Other researchers have documented effects of modifying conditions and process parameters of pure AA6061 gas atomized cold spray depositions including pressure [1], temperature [1,2], spray angle and substrate surface finish [3], and nozzle control and feedstock parameters [4]. Many of the studies achieve increased deposition qualities by ultimately increasing the particle velocity over a threshold critical velocity value [5]. Although costly and environmentally unsustainable, higher velocity values can be achieved by using helium as an alternative process gas to nitrogen [3]. Powder manufacturers have addressed this issue with the addition of ceramics such as Al_2O_3 or ZrO_2 increasing the cold spray performance of AA6061 powders by adding peening effects and minimizing kinetic energy transfer to previously deposited particles. To date, there is limited literature on ceramic-blended AA6061 powder. However, Ying-Kang et al. [5] studied a blend of gas-atomized AA6061 powder with micro-forging 410 stainless steel particles, which were large enough to remain below critical velocity. This resulted in a homogeneous AA6061 deposition. In contrast, commercially available ceramic blended powders contain particles that exceed critical velocity, leading to coatings with ceramic particles embedded throughout the deposited layer. Additionally, while most AA6061 powders are manufactured by gas atomization, newly available metallic powders with different manufacturing methods such as mechanical grinding offer alternative particle morphology and material properties. Mohankumar et al. [7] demonstrated the effectiveness of Response Surface Methodology (RSM) by optimizing feed rate, standoff distance, and temperature to enhance the adhesion strength of AA2024 coatings on AZ31B substrates. Building on this approach, this study applies RSM with a central composite design to investigate the influence of temperature and pressure on the deposition behavior of commercial five AA6061 powder variants (Table 1). The objective is to identify optimal conditions that maximize deposition efficiency, coating thickness, density, and hardness. RSM trial deposition characteristics provide additional insight on the effects of temperature and pressure on response variables. Comparisons are made between pure AA6061 gas atomized and ground powders, and blended gas atomized powders showing the effectiveness of ceramic additions and alternative powder manufacturing methods.

2. Materials and methods

Cold spray depositions were performed with powders listed in Table 1 using a CenterLine EPX cold spray system with maximum system limitations of 500psi and 500°C and a polymer nozzle for pure 6061 powders, and 600°C and a tungsten carbide nozzle for blended 6061 powders. Trial depositions for RSM were performed ranging from 300-500psi and 300-500°C for pure AA6061 powders, and 300-500psi and 300-600°C for blended 6061 powders. All depositions were performed with a nozzle stand off distance of 15mm, 1.2mm stepover, and 5mm/s tool speed depositing a single pass coating on grit blasted AA6061 extruded flat bar substrate with nitrogen carrier gas.

Table 1: Pure and blended 6061 powders used in study.

Powder	Manufacturer	Composition	Size Distribution [μm]	Production Method
SST A5012	CenterLine	AA6061	45-50	Gas atomized
SST A0079	CenterLine	AA6061+Al_2O_3	54-69	Gas atomized
6061	Metal Powder Works (MPW)	AA6061	20-63	Ground
SAAM 6061	Solvus Global	AA6061	35.5 +/- 10%	Gas atomized
DARC 6061	Solvus Global	AA6061+ZrO_2+SiO_2+Al_2O_3	45 +/- 10%	Gas atomized

RSM is performed with Minitab 21.1.0 with a central composite design with temperature and pressure explanatory variables, and deposition efficiency, thickness, density, and hardness response variables. Deposition efficiency was calculated from measured powder flow rate, deposition time, and deposition mass. Thickness was measured with digital calipers and measured from the substrate to the highest point of the deposition. Density was measured with a Sartorius scale and VF4601 density determination kit in accordance with ASTM B311-17. Microhardness tests were performed with a Clemex Automated Microhardness Tester at 10gf and 10 second dwell time. Each pure AA6061 hardness measurement is the average of 9 evenly spaced indents in accordance with ASTM E92-23, located midway through the thickness of the deposition. For blended powders the same initial indent pattern was used but individually re-located if the indent occurred over any ceramic.

3. Results and discussion

All powder varieties exhibit significant increase in deposition efficiency and coating thickness with increasing temperature, as anticipated [2,3,7], and slightly with pressure (Figure 2, Figure 3). Additionally, deposition efficiency and thickness are correlated, since higher deposition efficiency results in greater mass adhesion causing increase in overall deposition thickness. The increase in deposition efficiency and thickness due to the addition of ceramic is clearly significant with an increase from 3.16% to 11.19% and 0.68mm to 2.21mm respectively (Figure 2). These improvements are observed at system temperature and pressure limits when comparing A5012 and the blended A0079. The same, but weaker, trend is observed when comparing SAAM 6061 and DARC 6061 deposition efficiencies, while inconclusive results are seen for thickness were SAAM 6061 depositions over 400psi surpass the DARC 6061 thicknesses (Figure 3). Hardness results for gas-atomized powders have opposite trend of deposition efficiency and thickness where hardness slightly decreases with temperature increase. For the ground MPW 6061 hardness values are consistent at the highest temperature deposition at 500°C averaging 151 HV, and scattered results for depositions performed at 300°C and 400°C. Density measurements were consistently near to substrate density at 2.683 g/cm^3 for pure AA6061 powders and DARC 6061 as ZrO_2 percentage is insignificant, while averaging 2.744 g/cm^3 higher for A0079 due to the high percentage of Al_2O_3.

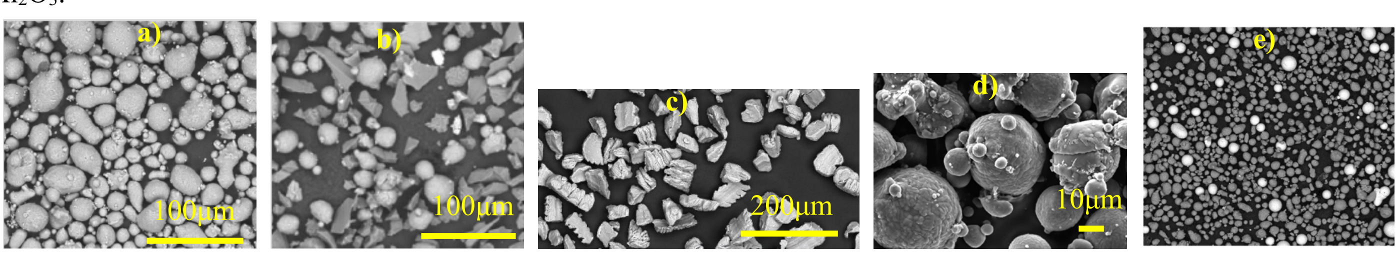

Figure 1: Powder images obtained from manufacturer data sheets with varying magnifications. a) A5012 spherical powder with satellite particles, b) A0079 spherical powder with satellite particles and added irregular-shaped Al_2O_3 particles, c) MPW 6061 mechanically ground satelite-free powder with irregular morphology, d) SAAM 6061 spherical powder with satellite particles, e) DARC 6061 spherical powder with spherical ZrO_2 particles (scale unknown)

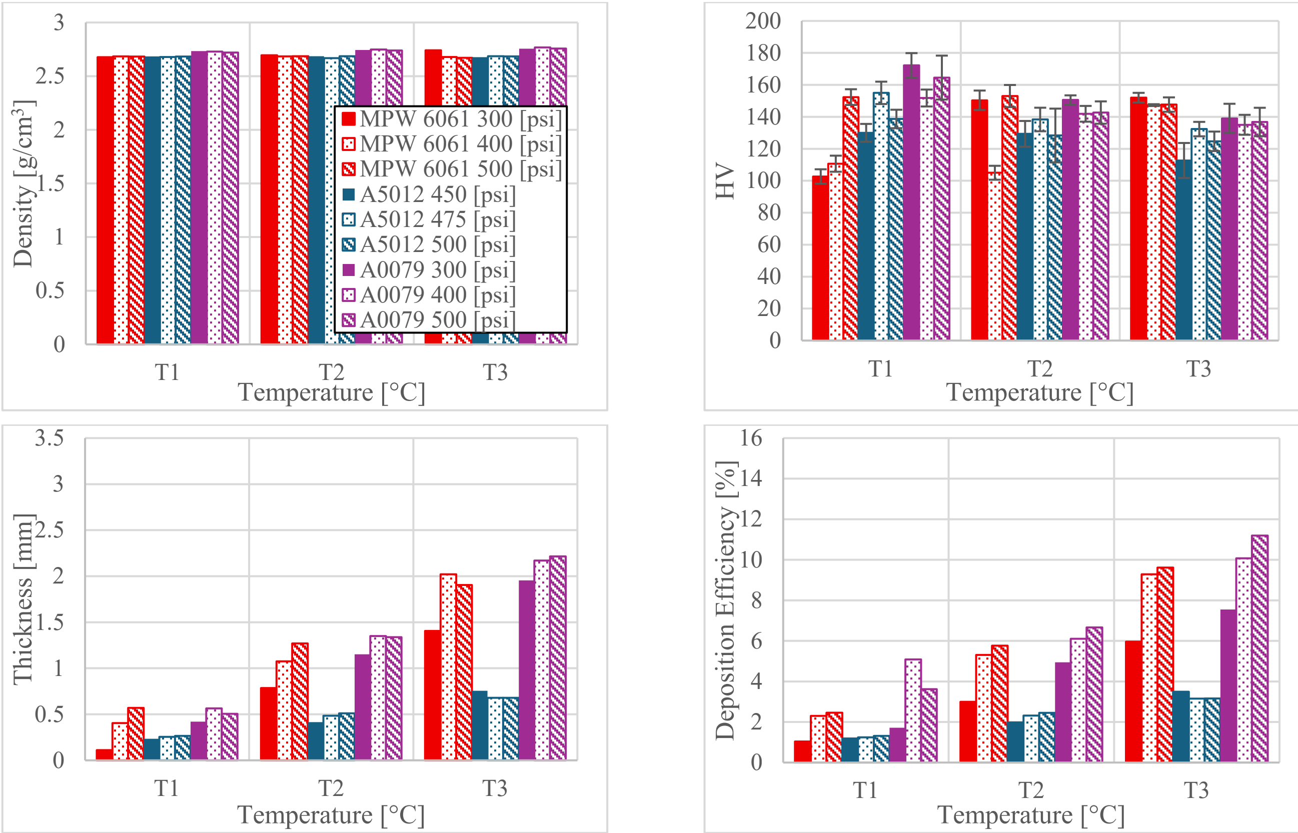

Figure 2: Deposition efficiency, thickness, density, and Vickers hardness plots for A5012, A0079, and MPW 6061 cold spray depositions. A5012 T1=400 °C, T2=450 °C, T3=500 °C, MPW 6061 T1=300 °C, T2=400 °C, T3=500 °C, A0079 T1=300 °C, T2=450 °C, T3=600 °C.

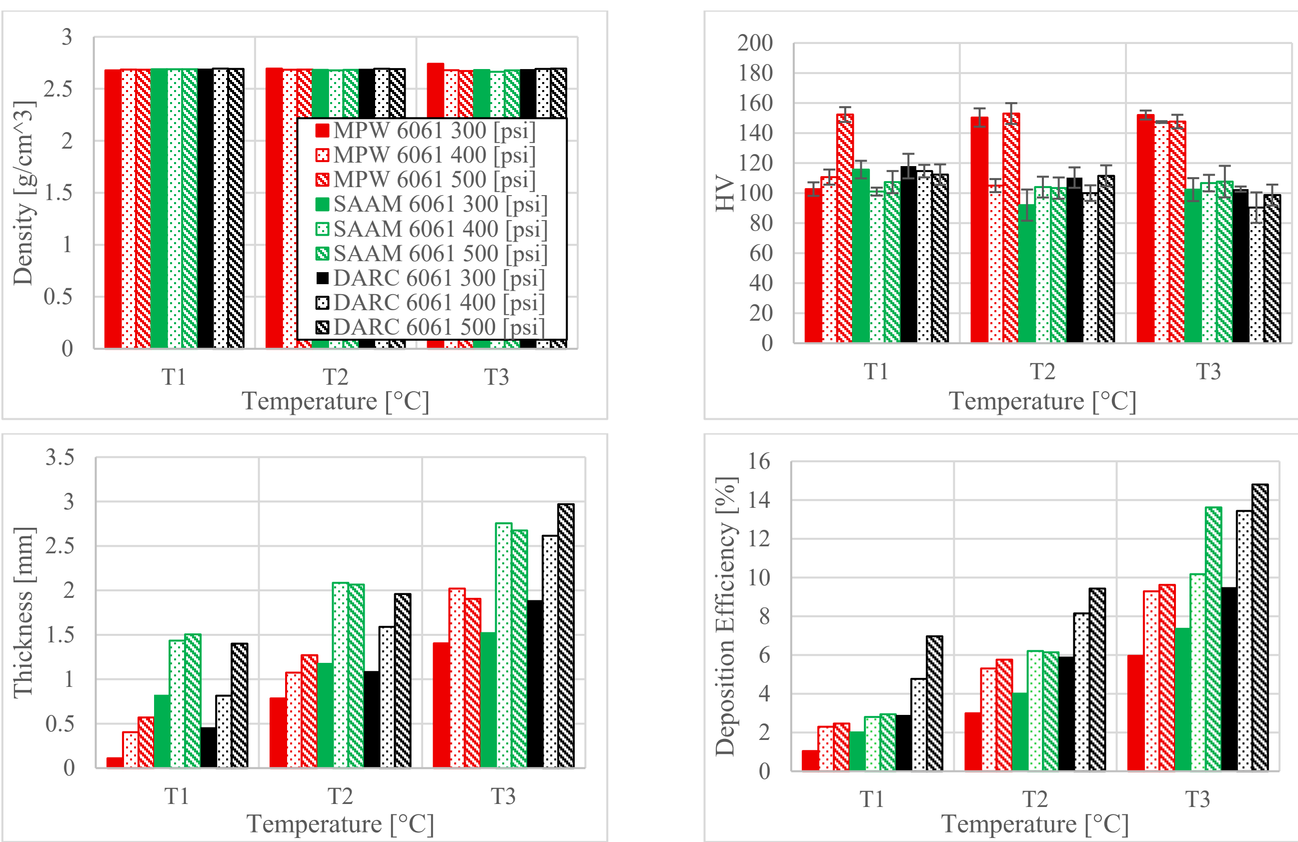

Figure 3: Deposition efficiency, thickness, density, and Vickers hardness plots for SAAM 6061, DARC 6061, and MPW 6061 cold spray depositions. SAAM 6061 and MPW 6061 T1=300 °C, T2=400 °C, T3=500 °C, DARC 6061 T1=300 °C, T2=450 °C, T3=600 °C.

When comparing A5012 and A0079 and their counterparts SAAM 6061 and DARC 6061 a trade-off of deposition efficiency and thickness with hardness is evident. Considering consistent morphology (Figure 1), assuming similar 6061 chemical compositions, and size distribution differences between A5012 and SAAM 6061, a conflict with the understanding that increase in particle diameter reduces deposition [8], the SAAM 6061 powder's lower critical velocity is likely attributed to gas atomization process parameter differences. The effects in addition to the substantial difference in powder composition observed in the higher ceramic content in A0079 compared to DARC 6061 further accentuate the trade-off between deposition efficiency and thickness, with hardness.

The mechanically ground AA6061 typically powder achieves significantly higher deposition efficiencies and thicknesses than A5012, excluding some depositions at the lower temperature and pressure conditions, and produced reasonable but thinner coating thicknesses compared to SAAM 6061. Although the hardness values of ground AA6061 are scattered under lower temperature and pressure conditions, the lower values remain comparable to those of SAAM 6061 and DARC 6061. At higher temperature and pressure conditions, however, ground AA6061 exhibits significantly greater hardness attributed to the strain hardening associated with the high plastic deformation manufacturing method.

Considering the deposition efficiency and thickness to hardness trade off, the optimum temperature and pressure values maximizing deposition efficiency, thickness, density, and hardness are obtained with RSM (Table 2) showing that the optimum temperature occurs at or near machine limits, and optimum pressure occurs throughout the deposition range. The density response was added to the RSM study with the intention to include the indirect porosity response but with added ceramics and alternative powder manufacturing methods skewing results, density was removed and resulted in less then a 0.1% change in optimum temperature and pressure conditions.

Table 2: Minitab RSM results with optimum pressure and temperature values, with corresponding estimated response values.

Powder	Pressure [psi]	Temperature [°C]	Density [g/cm^3]	Deposition Efficiency [%]	Thickness [mm]	Vickers Hardness	Composite Desirability
AA5012	487.4	500.0	2.681	3.23	0.69	131.4	0.71
AA0079	300.0	600.0	2.757	7.58	1.95	141.2	0.51
MPW 6061	318.2	500.0	2.722	6.76	1.57	153.6	0.78
SAAM 6061	500.0	500.0	2.674	13.14	2.73	110.6	0.51
DARC 6061	500.0	597.0	2.693	14.74	2.97	98.9	0.65

4. Conclusion

This study shows the effectiveness of blending ceramics with pure AA6061 gas atomized powders, as well as mechanically ground powder, in increasing deposition efficiency and thickness and quantifying the hardness trade-off. RSM shows that although critical velocities are met, optimization of process parameters is still required to obtain the highest quality depositions. Further microstructural analysis needs to be performed to determine differences amongst gas atomized AA6061 powders to fully correlate powder and deposition characteristics. The work in this paper is a preliminary step in determining optimum process parameters to compare gas atomized, ceramic blended, and mechanically ground powder cold spray depositions for cohesion and adhesion mechanical behaviour.

5. References

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