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The effects of heat treatment on 7075 Al cold spray deposits

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ABSTRACT

High-pressure cold spray was used to deposit 7075 aluminum powder onto 7075-T6 substrates. We investigated the effects of post deposition heat treatments on the microstructure and mechanical properties of the deposits. For this purpose, both low-temperature and high-temperature treatments were carried out on specimens excised from the deposits. Microstructures of the as-deposited and heat treated samples were characterized via different microscopy techniques and mechanical properties were evaluated by microtensile and hardness tests. The results were then correlated with the observed microstructures in different conditions. The strength and ductility of the cold sprayed 7075 deposits increased after both low- and high-temperature treatments, which resulted in precipitation of strengthening phases and increased inter-particle bonding. Because of a change in bonding mechanism, heat treatment at high temperature yielded markedly greater ductility than all other conditions. Diffusion and microstructural sintering at the particle-particle interfaces were proposed to cause the change in bonding mechanism from mechanical interlocking to metallurgical bonding and lead to the ductile characteristics of these samples. The understanding gained from this research should lead to optimization of and pre- and post-processing treatments for cold spray deposits.

1. Introduction

Cold spray (CS) has gained traction as a repair process, especially for components of military systems, where replacement costs and downtime are prohibitively high and long. Ideally, repaired parts should exhibit mechanical properties equivalent to or superior to the parent materials. However, while CS deposits generally show high strength because of the severe plastic deformation (SPD) intrinsic to CS, they often exhibit decreased ductility because of the extensive cold work and/or porosity in the deposit [1–4]. Effort has been made to improve the quality of the CS deposits by reducing porosity and thereby achieve superior combinations of ductility and strength [3–7].

High-pressure cold spray (HPCS) systems can address this problem by producing deposits with reduced porosity and improved ductility [2–8]. In addition to reducing porosity, HPCS also produces more extensive deformation compared with low-pressure systems, giving rise to ultra-fine grain (UFG) structures, particularly at prior particle boundaries (PPBs) [4,5,10–13]. According to the literature on various SPD processes [13–17], development of these UFG structures can also enhance the mechanical properties, e.g. strength, hardness and ductility, of the processed materials.

The strength of CS deposits can also be increased by introducing small precipitates through performing heat treatment (HT) in age hardenable alloys, such as 2xxx, 6xxx, and 7xxx Al [18–25]. This is because deformation prior to HT is commonly used to foster heterogeneous nucleation of precipitates in these alloys. This approach has been reported for 7xxx Al alloys after processing by SPD techniques [21–25]. One study on CS 7075 deposits [6] showed that deposits were strengthened by aging, yielding an increase of ~60 HV hardness after T73 heat treatment. Because CS is a relatively new SPD process used primarily for repairs, the effects of HTs on strength and ductility of the deposits warrants investigation.

High-temperature HTs of CS deposits, including annealing and solutionizing, reportedly increase the ductility, albeit at the expense of strength, which often decreases [26–32] because of grain growth. However, in situ microstructural observations have shown that solute segregation to grain boundaries (GBs) during heat treatment can stabilize UFG structures against grain growth [9,13,32]. In the present study, we also investigate on the effects of high temperature HTs on structure and mechanical properties of CS 7075 deposits.

CS is an SPD process, but compared with conventional wrought alloys that are sometimes stretched prior to aging, the deformation microstructure in CS deposits is much less homogeneous [2–4]. Thus, designing and optimizing a single HT for CS deposits may not be possible, and evaluating conventional HT's provides a useful starting point.

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The objectives of this study are to determine the effects of conventional and low- and high-temperature HTs on the microstructure and mechanical properties, including strength, ductility, and hardness. The approach employed involves analysis of precipitate morphologies in different regions of the CS 7075 Al deposit, and results are compared and contrasted with the properties of the as-deposited (AD) and bulk alloys. The 7075 Al alloy an age-hardenable alloy that is widely used for structural components in military and civilian aircraft, as well as in the automotive industry [32–34]. However, there have been no reports of the effects of HTs on the strength and ductility of CS deposits of 7075 Al. In this work, we report measured mechanical properties and correlate the values to corresponding microstructures after heat treatment using microscopy techniques. The fracture surfaces were also analyzed to assess bonding mechanisms in AD and HTed materials. Note that ductility is used as a critical performance metric for repairs implemented by CS, partly because ductility is readily measured. Also, ductility can contribute to fracture toughness, which is more difficult to measure, particularly for coatings.

2. Experimental procedure

2.1. Coating preparation

7075 Al coatings were produced using gas-atomized 7075 Al powder (Valimet, Stockton, CA, USA), 18.6 ± 8.2 μm in size. Feedstock powder size was measured using a laser diffraction particle size analyzer (S3000, Microtrac, Montgomeryville, PA). Helium process gas was used to achieve high impact velocities. The deposits were produced using a high-pressure cold spray system (VRC Gen III, VRC Metal Systems, Rapid City, SD, USA) and the pressure and temperature of helium were maintained at 2.8 MPa and 400 °C at the heater exit, respectively. Deposition was performed using a nozzle stand-off distance of 25 mm, 90° deposition angle, medium powder feed rate (12 g min^{-1}), and a nozzle traveling speed of 600 mm s^{-1}, yielding a total deposition thickness of ~8.5 mm.

2.2. Microtensile samples

Uniaxial tensile testing was carried out at room temperature with a loading rate of 200 μm/min in a universal testing machine (MTS 810, MTS Systems Corporation, Minneapolis, MN, USA). Tensile testing coupons were machined from the as-deposited cold spray samples with the dimensions shown in Fig. 1. These specimens were fine polished on both sides to remove/minimize surface defects, resulting in a final thickness of 1.0 mm. Specimens were machined such that the tensile axis was perpendicular to the spray direction. A total of 12 samples were tested, including three samples for each of the following conditions: as-deposited, stress relieved, T6 aged, and substrate material (bulk).

2.3. Heat treatments (HTs)

Six HTs were performed on as-deposited CS samples, including as-deposited (AD, no heat treatment), T6, solid solution treating + T6 (SS + T6), stress relief (SR), T7X, T73, as well as annealing treatments. These HTs are commonly used for 7075 Al alloys, and are summarized in Table 1. Note that the time and temperature used for all HTs were the same as those used for conventional HTs, although they are likely to be different for SPD alloys, i.e. CS deposits. All HTs were performed in an open air furnace (Lindberg 51894, Riverside, MI), and the 7075 Al substrate material was received in T6 condition.

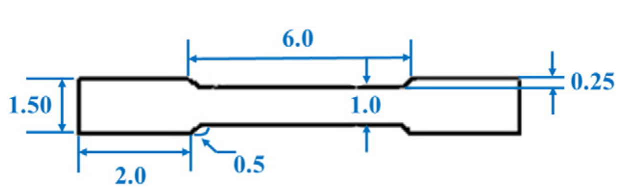

Fig. 1. Specimen geometry used for microtensile testing. All dimensions are in mm.

Table 1
Time and temperature conditions for the applied heat treatments [35].

Condition	Temperature (°C)	Time
AD	RT	8 months
T6	121	24 h
T73	107 + 163	6 + 24 h
T7X	107 + 163	6 + 4 h
SR	107 + 163	6 + 1 h
Annealing	412	3 h
SS + T6	450 + 121	
	12 + 24 h	

2.4. Microhardness testing

Vicker's microhardness measurements were performed on the CS 7075 Al material in as-deposited and heat-treated conditions, as well as on the bulk 7075-T6 material using a Vicker's microhardness tester (HMV-2, Shimadzu, Tokyo, Japan) and an indenter load of 300 g. For all the microhardness values reported, 15 measurements were performed, and the standard deviations were calculated.

2.5. Microstructure characterization

The microstructure of the as-received powder and CS deposits were characterized using transmission and scanning electron microscopy (TEM and SEM), as well as electron back-scattered diffraction (EBSD). TEM micrographs were obtained at 200 kV (JEM-2100, JEOL Ltd., Tokyo, Japan). Thin discs, 3 mm in diameter, were excised from the deposits, then polished, dimpled, and ion milled for 4 h. SEM and EBSD analyses of the as-received powders and cold spray deposits were conducted using a field emission SEM (Supra-40, Zeiss, Oberkochen, Germany) operated at 15 kV. EBSD samples were sectioned from the CSP deposition and prepared by standard metallographic techniques. Final polish was conducted using 0.05 μm colloidal silica suspension and vibratory polishing.

3. Results and discussion

3.1. Powder characterization

Fig. 2(a–b) show SEM images of the as-received gas-atomized 7075 Al powder. The particles are spherical with diameter 18.6 ± 4.2 μm. The powder size distribution consists of a mixture of both large (~10–20 μm) and micro-satellite particles (less than 5 μm in size). Fig. 2(b) shows a typical powder particle of ~20 μm, with ~1–4 μm external grain structure. Details of the internal and surface microstructures of the powder particles have been reported [3].

3.2. As-deposited material

Microstructural characterization of CS deposits prior to ageing was carried out, and Fig. 3 shows typical pattern quality EBSD maps obtained from the CS 7075 Al deposit. Overall, the CS deposit exhibits no evidence of porosity, triple junction voids, or lack of bonding between powder particles. The absence of such defects indicates that the deposition parameters selected resulted in sufficient particle deformation. Indeed, the originally spherical particles have undergone extensive plastic deformation, as indicated by the dashed lines. The SPD during deposition led to three distinct microstructural regions: 1 - particle interior (dashed white line), 2 - PPBs with pancake morphology (red arrows) and 3 - PPBs with recrystallized UFG structures (white arrows). The