Solid-State Spray Forming of Aluminum Near-Net Shapes

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Authors' Note: In this article, a metal-matrix composite refers to any solid-state spray-forming material that comprises aluminum and any reinforcement or strengthening material.

INTRODUCTION

Osprey and low-pressure plasma spray (LPPS) are two liquid-phase spray-forming processes used to produce aluminum and aluminum metal-matrix composites (MMCs). The Osprey process is a method for spray forming aluminum components[1–3] that uses sequential stages of atomization and droplet consolidation. Invented in 1970, the Osprey process is controlled by Osprey Metals of Neath, Wales. Licensees for aluminum deposition include Alcan (United Kingdom), Peak (Germany), Alusuisse (Switzerland), Pechiney (France), Sumitomo Light Metals (Japan), and Alcoa (United States).[4] To improve the performance of the traditional Osprey process, recent research conducted at the Idaho National Engineering Laboratory focused on using De Laval nozzles. High-speed deposition of liquid droplets with De Laval nozzles is the liquid analog of the solid-state spray-forming (SSF) processes.

LPPS, a variation on vacuum-plasma spray that is sometimes referred to as controlled-atmosphere plasma spray, was developed during the same time period by Erich Muehlberger at Electro Plasma.[5] LPPS is well established for producing ultrahigh-quality coatings. It is less frequently used for spray forming and is under investigation for depositing aluminum MMCs.[6]

MMCs produced with the liquid-phase processes exhibit extremely fine grain size and uniformly distributed strengthening particles. These attractive metallurgical features are somewhat allayed because post-deposition thermomechanical treatment must be performed to obtain peak mechanical properties. However, the major drawback for the processes is capital equipment cost. The minimum equipment costs for both the Osprey and LPPS processes are estimated to be $2 million. High utility and mechanical-maintenance costs are also associated with these processes.

Several conventional methods are also available for producing near-net-shape aluminum components, including die casting and forging[7] and powder metallurgy. These processes require significant tooling investments and are not applicable to producing aluminum MMCs. Additionally, die-cast parts are low in strength and ductility. The extrusion of aluminum MMCs is a viable process, but near-net shapes are restricted to continuous profile parts and, thus, have only limited uses.

SPRAY FORMING ALUMINUM NEAR-NET SHAPES

SSF is a new approach to forming free-standing aluminum and aluminum MMC shapes. The concept is energy-efficient and ecologically sustainable. Like conventional (liquid/near-liquid phase) spray forming, SSF can produce finished parts that require a minimum of tooling and machining. Unlike conventional techniques, SSF does not consume energy to melt the aluminum. Because the process is performed completely in the solid state, the resultant parts are expected to exhibit material properties closer to those of wrought, rather than cast, alloys. Table I compares the SSF, LPPS, and Osprey processes.

Table I. Three Processes for Spray Forming Aluminum

Feature	Solid-State Spray Forming	Low-Pressure Plasma Spray	Osprey
Feedstock	Powder	Powder	Bulk
Entrainment	Fluidize	Fluidize	Atomize
Gas Flow	Very High	High	High
Gas Type	Air, Helium, Steam	Ar/H_2	Argon
Particle Speed	Very High	High	Slow
Setup	Minimal	Extensive	Extensive
Atmosphere	Ambient	Vacuum	Chamber
Reworkability	Yes	No	No
Cost	Low	High	High
Temperature	Low	Very High	High

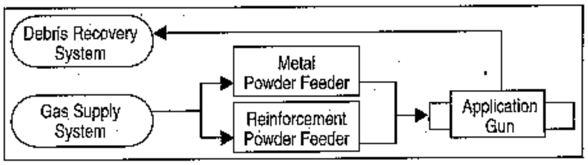

Figure 1. The SSF system for fabricating aluminum MMCs.

SSF parts are formed at low temperature, and, therefore, the sprayed metal or alloy remains metallurgically unaltered. Unstable or otherwise impractical strengthening phases (including nanophase particles) may be added simply by mixing powdered forms of these materials with the feedstock. For example, MMCs composed of standard aluminum-alloy matrix and ceramic-reinforcement particles are expected to be formed as finished or near-finished parts. The production of multiple layers of functionally graded material may also be deposited without thermal degradation or chemical interaction.

SSF is performed with a patent-pending process developed by Innovative Technology.[8] It uses a specially designed, two-phase, converging–diverging deposition nozzle to accelerate metal particles entrained in a gas. The gas/particle suspension is directed onto a substrate or a mandrel or into a mold. The high-speed collision of the metal particles causes very large strain in the particles, which produces large, oxide-free contact areas. When these active surfaces come into contact, true metallurgical bonds are formed. Metallurgical bonding is achieved exclusively through solid-state reaction, bulk melting does not occur. Figure 1 schematically represents the SSF apparatus configured for spraying aluminum MMCs.

Debris generated during the SSF process is removed with a coaxial suction nozzle, driven by a debris-recovery system. The debris-recovery system filters contaminants from recovered effluent gas and allows excess powder to be recycled. SSF equipment is simple and, therefore, less expensive to manufacture and use than other processes. The SSF process is ecologically sustainable because it uses powders in the solid-state form and a debris-recovery nozzle, resulting in a nonpolluting manufacturing process.

Figure 2 shows a SSF deposition nozzle without the surrounding coaxial debris-recovery nozzle. The nozzle is fabricated from tungsten carbide to reduce wear, which is anticipated to be a problem with ceramic and other hard reinforcement particles. This nozzle was also used to create the first SSF samples (titanium, zinc, and copper) that were produced for the Lawrence Livermore National Laboratory.[9,10]

Brass and stainless-steel versions of the deposition nozzle were initially used in the kinetic-energy metallization process, which is used to produce thin metal coatings.[11] SSF differs from the coating process in that the system is optimized for the faster overlapping strokes required to spray thick, free-standing shapes. In a simple manifestation, SSF is used to produce aluminum and aluminum MMC tubes (Figure 3). Here, the mandrel is rotated while the gun traverses in and out of the plane of the page.

A unique feature of SSF is that it permits pinnacle or pyramid fabrication without liquid splatter, rebound, or form slumping. This feature allows near-net-shape components to be formed without supporting molds. In addition, because SSF is a directed and collimated spray technique, overspray is substantially less than that of the Osprey or LPPS processes. This feature is expected to reduce material and energy waste and allow damaged near-net-shape parts to be reworked or repaired.

ECONOMICS AND MARKET POTENTIAL

The cost of operating a small SSF nozzle (1.6 mm throat) using air heated up to 500 K is $3–5 per hour for the power (30 kW) required to run the compressor and the gas heater. A theoretical SSF deposition rate of 2.6 kg/h yields an electrical energy cost of $1–2/kg of deposited material. All of these numbers will scale in proportion to the nozzle-throat area.

The specific energy required for the air-heated SSF process is –41.5 MJ/kg. This compares favorably to the LPPS process, which requires 96–135 MJ/kg at a deposition rate of only 1.2 kg/h and a power consumption rate of 32–45 kW.[6] To sustain the plasma, the LPPS method typically uses argon gas flowing at a rate of 45 R/min. Thus, argon gas alone can cost as much as $10–20/kg if it is not recycled. If it is recycled, argon costs could be $1–2/kg.

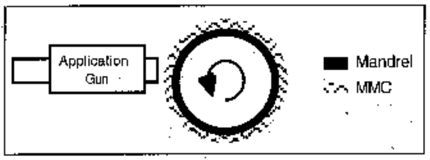

Figure 3. The SSF configuration for producing a MMC tube over a mandrel.

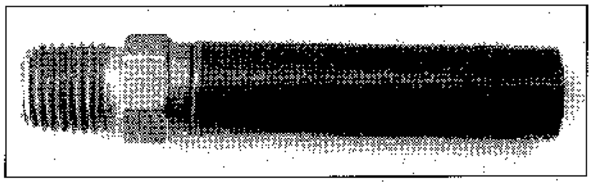

Figure 2. An SSF tungsten-carbide deposition nozzle with fitting.

LPPS and SSF both use metal powders as feedstock material. Thus, the deposition cost per kilogram of aluminum for the LPPS process (gas recycling) is between $8–18/kg, compared with $1–2/kg projected for an air-heated SSF system. In addition, the capital-investment cost for an SSF system is estimated to be an order of magnitude less than that of the LPPS system.

The Osprey process is capable of extremely high production rates for aluminum alloys, ranging from 0.2–2.0 kg/s.[3] Based on the energy required to melt aluminum and a 50 percent deposition efficiency, the Osprey process's specific energy requirement is 1,920 kJ/kg of deposited material. While this low specific energy is economically attractive, the electrical power requirements for an Osprey plant are enormous, ranging from 384 kW to 3.8 MW, depending on the deposition rates. Spray forming aluminum MMCs with the Osprey process has been accomplished through the injection of reinforcement particles (typically 5–10 μm SiC or Al_2O_3, up to 20% by volume) into the molten-metal feedstock. While demonstration studies were successful, sufficient deposition rates for scaling up to commercial production are not established.[12]

For traditional reinforcement particles (e.g., SiC or Al_2O_3), SSF is not expected to be cost competitive with the Osprey process. However, Osprey was developed mainly to spray form sheet material, not individual parts. More importantly, as a high-temperature, liquid-phase process, the Osprey process is not applicable to the spray forming of aluminum with new strengthening phases, including, but not limited to, nanophase particles. Moreover, the capital-equipment cost for even a small-scale Osprey plant is at least an order of magnitude higher than for an SSF facility.

Near-net-shape SSF aluminum and aluminum MMC parts are applicable to several markets, including automotive, aerospace, bicycles, electronics, heat exchangers, and rapid prototyping. The automotive, aerospace, and electronic industries require a wide range of aluminum components in various shapes.[13]

KEY EXPERIMENTAL RESULTS

The initial approach of this work was to test the validity of the SSF apparatus for producing free-standing aluminum shapes. Aluminum powder in a size distribution of less than 10 μm diameter was accelerated with helium at a driving pressure of 1.38 MPa. Later, aluminum MMC deposition was attempted.

Pure Aluminum

Figure 4 is an aluminum sample that was formed into near-net shape from powder with SSF. The near-rectangular flat was obtained by traversing the nozzle across the substrate with overlapping, painting-like strokes. This sample represents SSF buildups of 0.64 cm and is 10.16 cm long and 1.28 cm wide. A scanning electron micrograph of a cross section of this aluminum sample is shown in Figure 5. This sample is in the as-deposited condition (no post-deposition heat treatment). Note the highly deformed particles and the well-defined particle boundaries. The lower portion of the micrograph shows the K662 aluminum substrate.

A white-light micrograph of a cross-section of an aluminum SSF sample after it was annealed and etched is shown in Figure 6. This sample was annealed at –750 K for four hours to determine if excessive grain growth would occur; this was not the case. The figure also illustrates the contrast between the metallurgical characteristics of the aluminum SSF deposition (top) and the K662 substrate. Note the extremely fine grain size of the SSF deposition. The micrograph also shows extremely low porosity in the SSF-deposited material. The

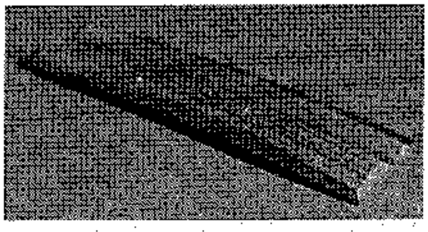

Figure 4. A pure aluminum SSF free-standing shape.

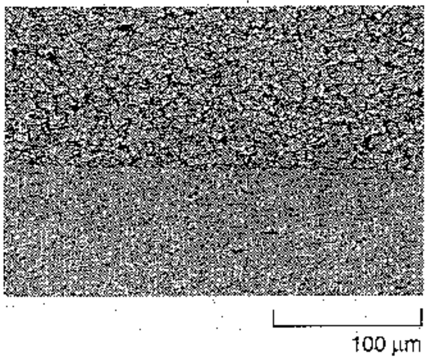

Figure 5. A backscatter scanning electron micrograph of an aluminum SSF sample.

Figure 6. A white-light micrograph of an annealed and etched aluminum SSF sample.

mechanical properties of this sample were not available at the time this article was published.

Innovative Technology is evaluating methods of eliminating the post-deposition annealing process. Heated air is one approach for both reducing the expendable costs of SSF and at the same time rendering the powder particles sufficiently ductile to diminish the degree of work hardening induced by the deposition process. In addition, Innovative Technology is investigating an auxiliary proprietary process that renders the annealing step unnecessary and allows for the direct near-net-shape spray forming of aluminum.

Aluminum MMCs

Strengthening-phase powders were mixed with aluminum powder (less than 10 µm diameter) in a ratio of one part strengthening phase to two parts aluminum. Two strengthening phases were investigated: SiC 400 mesh and SiC 60 mesh. Additional work was planned with Al_2O_3 strengthening-phase powders, but was discontinued based on the results.

Deposition rates for these materials were extremely low. Apparently, these hard particles act primarily as abrasives during the collision process and tend to remove the aluminum deposit as fast as it occurs. No MMC material was produced.

SSF deposition produced with other difficult-to-deposit (high hardness/low ductility) materials suggests an alternative approach to aluminum MMC deposition that will be attempted in future work. In this approach, specially prepared strengthening-phase powders that better match the mechanical impedance of aluminum will be used.

CONCLUSIONS

The next steps in developing SSF will require sufficient funding to produce samples with the suggested refinements and evaluate these samples. The steps include developing a proprietary auxiliary process that renders the annealing step unnecessary and allows for the direct use of the near-net shape in the as-sprayed condition, investigating specially prepared strengthening phase powders that better match the mechanical impedance of aluminum for producing near-net-shape aluminum MMC, using heated air as an accelerating gas, and conducting additional mechanical tests of aluminum and aluminum MMC to determine material properties.

After this work is completed, a production-prototype SSF system must be manufactured. Finally, to complete the SSF commercialization process, either a production facility or agreements with contract producers will be required. Innovative Technology anticipates that the SSF technology will also be licensed for use in various manufacturing plants. While it is too early to estimate the cost of these tasks, they will be considerable. The feasibility of such an expense will be evaluated on the basis of preliminary technical results, the market opportunity that the technical results suggest, and market-penetration estimates.

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