

Spray Deposition of MMC Composites by Laser Spraying with Particle Co-injection

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Abstract

The incorporation of ceramic particles in a spray deposited MMC composite material was investigated. Small Al/Al₂O₃ and Al/SiC deposits were obtained by laser spraying of aluminum with powder co-injection. The gas-metal-ratio and the type of powder have been the principal parameters varied in the study. The volume fraction of incorporated particles depended strongly on powder type and spraying parameters. Al/SiC MMC composite materials with a particle content of up to 30 vol.% were obtained. Particles were found to reside on former droplet boundary networks. From this observation, and the investigation of droplets that solidified during flight, it was concluded that the incorporation of particles into the MMC deposit occurred predominantly by a mechanical entrapment mechanism during deposition, whereas in-flight composite formation mechanisms were negligible.

Introduction

Particle reinforced Metal Matrix Composite (MMC) materials are obtained by spray deposition techniques. The method involves the atomization of molten metal into a spray of small droplets that is accelerated towards a collector. Solid particles may be added to the spray by injection of powder into the spray cone. Both metal droplets and reinforcement particles are deposited on the collector and form a compact MMC material. However, it is generally intended to achieve a high deposition efficiency of both species and a homogeneous distribution of the particles in the deposit.

Particles that reach the surface of the deposit are likely to be incorporated by mechanical entrapment during the impingement of metal droplets (Fig. 1). As a consequence, particles will be located on the boundaries of former spray droplets. For a more homogeneous distribution in the material, penetration of reinforcement particles into spray droplets is required either in-flight or during deposition. The in-flight formation of composite droplets occurs due to collisions of metal droplets with powder particles in the spray cone. As a result of collisions, particles may adhere to the surface of droplets or penetrate into the droplets. In an effort to elucidate significant penetration criteria, models have been established that identify the relative

size, velocity and density of particles and droplets, the wettability and a number of temperature dependent material properties including the viscosity [1,2]. However, there is a comparatively small number of supporting conclusions from direct experimental observation [3]. The present work uses a laser wire spray process in an experimental approach to study the incorporation of particles during co-injection and deposition.

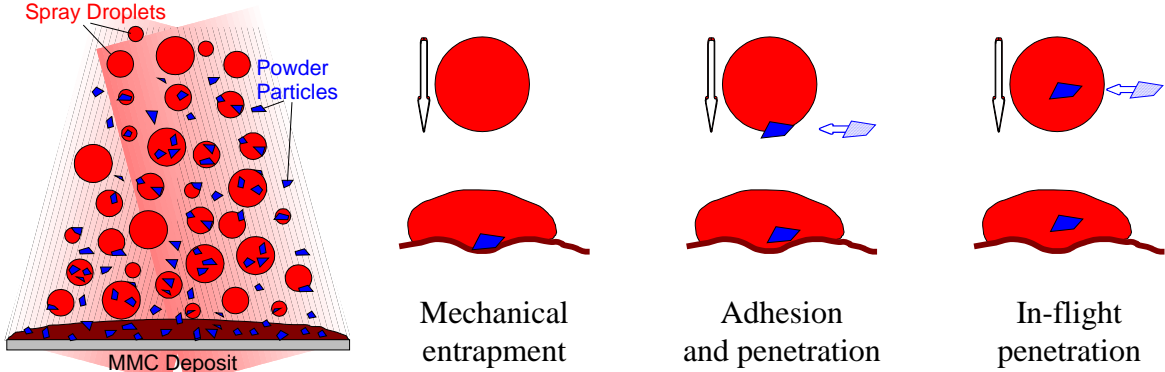


Fig. 1: Spray deposition of MMC composites by incorporation of co-injected powder particles

Laser spraying with particle co-injection

Principle of laser spraying

In the laser spraying process, a consumable wire is melted by a focused high power laser beam. The melt is disintegrated into small droplets and accelerated by coaxial gas jets to form a spray cone that propagates towards a target, Fig. 2.

Basically, all metal or alloy wire feedstock may be processed by laser spraying using inert or reactive gases. The yield of the process is limited by the laser power available for the melting of the wire. It is in the order of 10 g/min in the case of the 2 kW Nd:YAG laser used here, which is less than for other thermal spray processes. The laser intensity is kept below the threshold of plasma formation, so that the process gas is not involved in the transfer of heat for melting. Independent process parameters are the metal and gas flow rates and the laser power.

Experimental procedure

In this investigation, the laser spraying process was conducted in a controlled atmosphere chamber that was evacuated and filled with process gas before each experiment. Inside the chamber, a two-axis stage

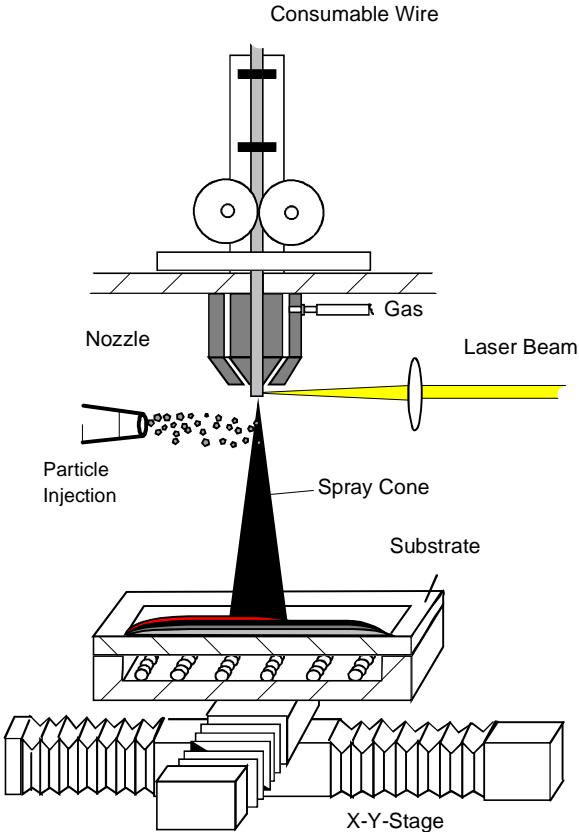


Fig. 2: Experimental set-up

was used to move a substrate plate relative to the spray cone in a meandering fashion. A 99.5% purity aluminum wire was sprayed using an argon/oxygen gas mixture (see Table 1). The particle size distribution (by sieve analysis) of the aluminum sprayed at different Gas Metal Ratios (GMR) is given in Fig. 3. The mass median d_{50} of the log-normal distribution is in the range of 50 to 120 μm .

Alumina and silicon carbide powders were co-injected into the spray cone. The particle size of these powders was smaller than the median of the aluminum spray. The powders (blocky thermal spray powders) were fed from a pneumatic powder feeder and injected perpendicularly into the spray cone using a single injector nozzle arranged 15 mm downstream from the atomization point. In a series of experiments, the GMR was varied with all other parameters kept constant (Table 1).

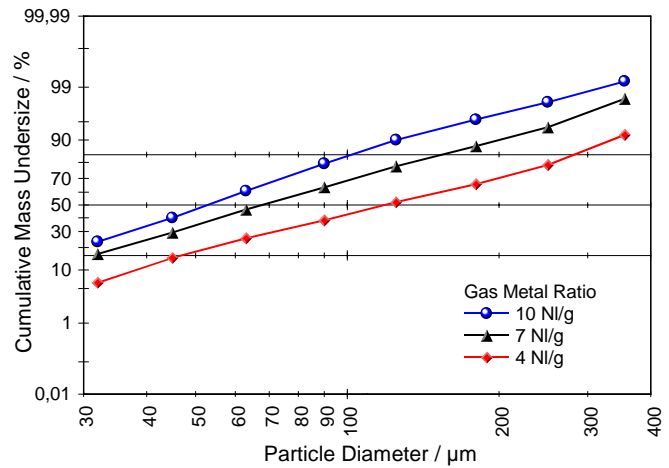


Fig. 3: Particle size distribution of laser sprayed aluminum (sieve analysis)

Table 1: Materials and process parameters

Spray process		Substrate movement	
Consumable wire:	Al 99,5, \varnothing 1,6 mm	Spray distance:	100 mm
Mass flow rate:	8,1 g/min	Scanned area:	60 mm * 60 mm
Process gas:	Ar/O ₂ 97/3	Scan offset:	5 mm
Gas Metal Ratio:	4 / 7 / 10 NI/g	Velocity:	12,5 mm/s
Laser power:	1,7 kW	Number of layers:	7
Beam diameter:	1,2 mm		
Particle injection			
Powder type:	Al ₂ O ₃ /TiO ₂ 97/3	SiC	SiC
Trade name:	Praxair ALO105	Praxair A WV1-125	GTV 70.85.0
Particle size:	-53 +10 μm	-40 +5 μm	-25 +5 μm
Feed rate:	9 g/min	9,7 g/min	7 g/min

Results

Effect of gas metal ratio and powder type

Deposits sprayed onto ceramic substrates were cross sectioned and prepared metallographically. Optical micrographs of the cross sections are given in Fig. 4 to 7. In a line from left to right, the GMR is 4, 7, and 10 NI/g, respectively. Spraying Aluminum without co-injection of particles (Fig. 4), a lamellar structure is observed with typical features of thermal spray products like interlamellar porosity and incorporations of droplets which were solidified during flight. With increasing GMR, smaller droplets hit the substrate at higher velocities, resulting in a smaller overall porosity and a smaller size of the individual pores. The overspray, i.e. the fraction of the sprayed material that does not contribute to the formation of the deposit, is between 16 and 22%.

The co-injection of aluminum oxide particles into the spray cone with all other parameters unchanged, results in an increased porosity in the deposit (Fig. 5). The volume fraction of particles in the deposit, however, does not exceed 4%. These experiments have been repeated using a number of different Al_2O_3 powders. In all cases, the yield was unsatisfactory.

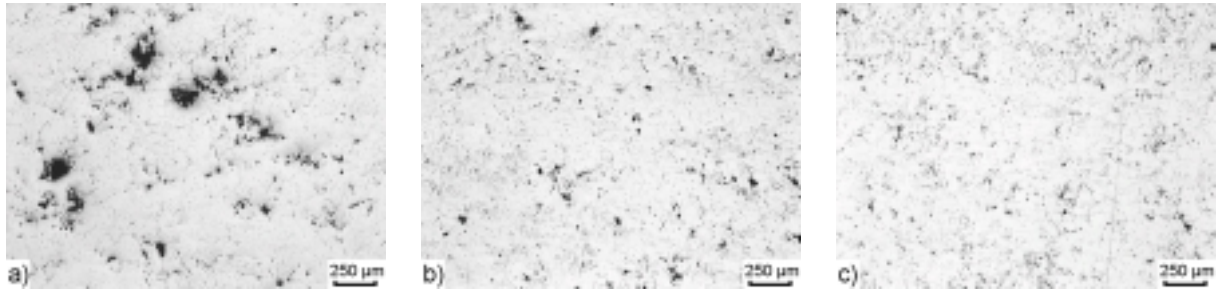


Fig. 4: Aluminum, sprayed with a GMR of 4, 7, and 10 NI/g

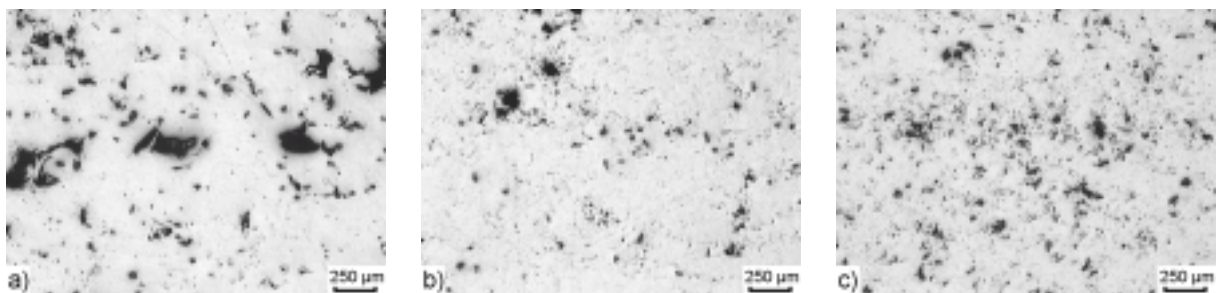


Fig. 5: Aluminum with Al_2O_3 (-53 + 10 μm), sprayed with a GMR of 4, 7, and 10 NI/g

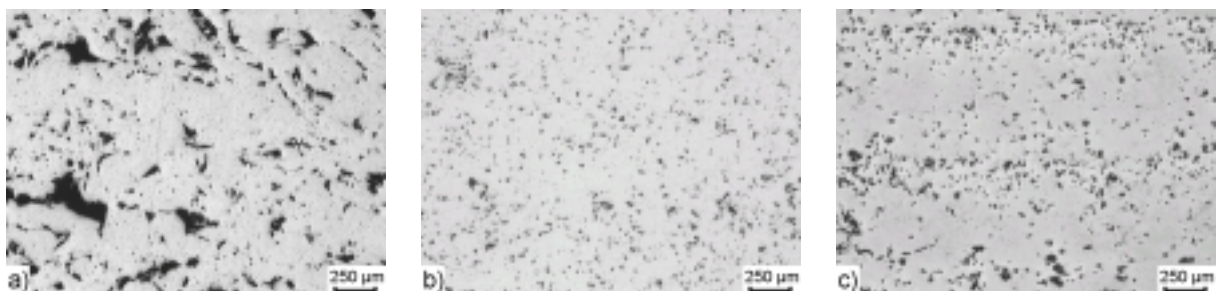


Fig. 6: Aluminum with SiC (-45 + 5 μm), sprayed with a GMR of 4, 7, and 10 NI/g

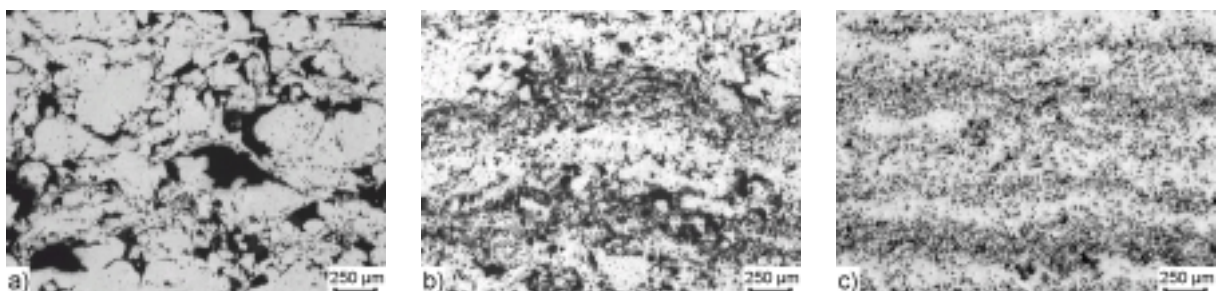


Fig. 7: Aluminum with SiC (-25 + 5 μm), sprayed with a GMR of 4, 7, and 10 NI/g

Higher particle volume fractions of up to 7% are observed in the case of silicon carbide powder co-injection, Fig. 6. In contrast to Al_2O_3 , SiC particles are expected to be wetted more easily by the aluminum droplets. Spraying with a small GMR (4 NI/g) leads to a further increase in porosity, Fig. 6a. Particles are present on the network of former droplet boundaries. With increasing GMR (7 NI/g), porosity is reduced significantly. The overall SiC particle distribution is homogeneous (Fig. 6b). At a GMR of 10 NI/g, an inhomogeneous distribution

with particle-rich and particle-depleted zones is observed, Fig. 6c. This can be attributed to the relative movement of the substrate with respect to the spray cone, which causes a layer-by-layer deposition. The SiC content is not constant within each layer. In the vicinity of the interface between subsequently deposited layers, the particle concentration is higher than in the central region of each layer. However, the locus of particle incorporation is the boundary of former aluminum droplets in all cases.

Using a SiC powder of smaller particle size (Fig. 7), the amount of SiC particles incorporated into the deposit is increased significantly. Porosity is largely affected, particularly at a GMR of 4 NI/g. An inhomogeneous (layered) particle distribution is evident from the micrographs (Fig. 7b). However, at a GMR of 10 NI/g the observed particle distribution is more uniform, and the particle volume fraction increases to a considerable 25 %.

Effect of substrate temperature, spraying distance and gas type

A number of experiments were conducted with co-injection of the fine SiC powder at a GMR of 7 NI/g (compare to Fig. 7b) using a substrate plate heated to 550 °C. As a result, the SiC content of the deposit is up to 30% (Fig. 8a). Moreover, porosity is reduced and the homogeneity of the SiC distribution is improved in such a way that particle-rich zones grow at the expense of particle-depleted zones. The layered structure can be avoided by varying the spray distance e.g. from 100 to 140 mm (Fig. 8b).

All aforementioned experiments were conducted employing an Ar/O₂ gas mixture. Running the process with pure argon (on room temperature substrate) was found to have an effect neither on the yield of particles incorporated in the deposit nor on the homogeneity of their distribution, Fig. 8c. However, the porosity of the deposit is reduced due to an improved bonding at the boundaries of the former aluminum droplets.

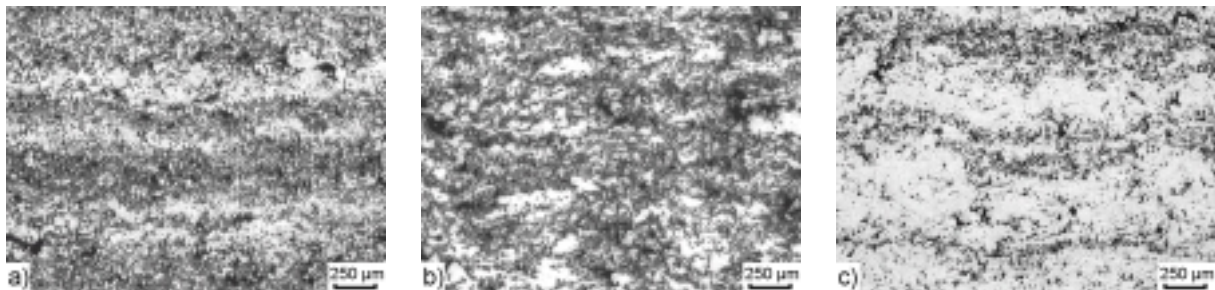


Fig. 8: Aluminum with SiC (-25 + 5 μm), sprayed with a GMR of 7 NI/g
a) onto heated substrate at 550 °C at a distance of 100 mm
b) onto heated substrate at 550 °C at a distance of 140 mm
c) onto cold substrate with pure argon process gas

Conclusions

Laser spraying of aluminum with particle co-injection enables the deposition of MMC composite materials with a particle fraction of up to 30 vol%. Under the conditions investigated here, the yield and distribution of particles in the deposit varies with the gas metal ratio and the type of powder used. Comparing two SiC powders of different particle size reveals that smaller particles are more efficiently incorporated. The small yield of aluminum oxide powders is attributed to their comparatively large particle size and the poor wetting behavior.

The microstructure of the MMC deposits is characterized by particles residing predominantly on the boundaries of former aluminum droplets, Fig. 9a. At higher volume fractions, particles decorating these boundaries form a necklace type of distribution with a high degree of parti-

cle-particle contact and entrapped inter-particle porosity. With increasing GMR, the size of the spray droplets is reduced, thus the microstructure is finer, and more boundary space is available for incorporation of particles.

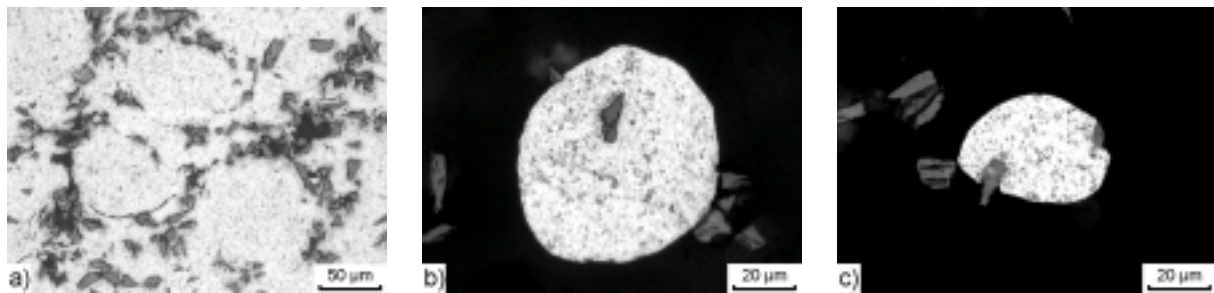


Fig 9: Aluminum with SiC (-25 + 5 μm), sprayed with a GMR of 7 NI/g
a) Necklace type distribution of SiC particles on former Al droplet boundaries
b) Composite droplet with SiC particle (in-flight penetration)
c) Composite droplet with adherent SiC particles

Investigating micrographs of spray particles that have been collected after in-flight solidification (instead of deposition onto a substrate), composite droplets containing SiC particles fully incorporated in aluminum are very rarely observed (Fig. 9b). More frequently, adherent or partly penetrated SiC particles are present on the surface of composite droplets (Fig. 9c). Although evidence of in-flight formation of composite particles is found, it is concluded that under the given conditions the incorporation of particles into the MMC deposit occurs predominantly by the mechanism of mechanical entrapment during deposition (compare Fig. 1), whereas composite formation by adhesion and penetration and in-flight penetration mechanisms, respectively, are likely to be negligible.

The effect of thermal energy at deposition is indicated by experiments using a heated substrate. Further investigations will focus on this effect, and on the co-injection of particles of higher density and velocity in order to approach the effect of the impulse on composite formation.

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