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Effect of a novel sequential motion compaction process on the densification of multi-layer spray deposited 7090/SiCp composite

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Abstract In the present study, a large dimension Al–10.15Zn–3.6Mg–1.8Cu–0.15Ni–0.3Zr/SiCp composite was synthesized by the multi-layer spray deposition process, then densities by a novel sequential motion compaction technique. The microstructures and mechanical properties of the multi-layer spray-deposited Al–10.15Zn–3.6Mg–1.8Cu–0.15Ni–0.3Zr/SiCp composite were studied by optical microscopy, scanning electron microscopy, and tensile tests before and after densities. The experimental results showed that sequential motion compaction technique can be used to fully density sample with large dimensions and difficult to further processing by the traditional techniques. This technique can greatly improve the microstructures and mechanical properties of the composite. The pores in the composite are elongated and closed through model pressing at the jointed effect of huge hydrostatic pressure and shearing stress. After pressed, SiC particles in the composite were broken and redistributed. Compared with the as-spray-deposited composite, the tensile properties of compaction processed composite have a great improvement not only in transverse direction but also in longitudinal direction. When the thickness reduction is about 40%, relative densities approach the theoretical density, and the actual relative density is 91.76%. The relative theoretical density is 93%.

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Introduction

Particulate reinforced aluminum matrix composites have received much research interests over the last two decades due to their excellent yield and tensile strengths, high specific elastic modulus and isotropic properties, which makes them one of the best structural materials in the fields of aerospace, automotive, electronics industry, etc. [1–3].

Spray deposition technology was first developed by Singer in Swansea University in the 1970s [4], and was further developed by Chen et al. [5] in the 1990s. It has been recognized generally that the spray-deposited process is an innovative technique of rapid solidification. In this process, droplets are first atomized from a molten metal stream, quickly cooled by an inert gas, then deposited on a substrate, and finally built up to form a low-porosity deposit with the required shape, which can be used to produce materials with fine-grained microstructure less or no composition segregation in the matrix due to the high cooling rate, and have advantages over the conventional casting techniques [6–8]. However, spray-deposited materials usually exhibited poor mechanical properties if without further plastic working for the porosity [9].

In order to improve the mechanical properties of the as-deposited composite, it is necessary to obtain a fully densities composite first, the porous spray deposited perform must be further densitied along with some plastic working, such as forging, extrusion, rolling, etc. Densification of porous metal performs by hot working requires shearing deformation to eliminate the pores [10].

The present work was aimed at investigating the microstructural evolution of multi-layer spray-deposited Al–10.15 Zn–3.6Mg–1.8Cu–0.15Ni–0.3Zr/15vol.SiCp composite during a novel sequential motion compaction processing and heat treatment, and its impact on the mechanical properties of the final product at room temperatures.

Experimental

In this article, the nominal composition of 7090 matrix alloy was 10.15 wt% Zn, 3.63 wt% Mg, 1.8 wt% Cu, 0.15 wt% Ni, 0.3% Zr, balance aluminum. The average diameter of SiC particles is about 10 μm, and the volume fraction is controlled at about 15 vol%, which served as the reinforcement. The multi-layer spray deposition experiments were conducted in an environmental chamber. A summary of the primary processing parameters used in the present study is provided in Table 1. A schematic diagram of the multi-layer spray deposition equipment is shown in Fig. 1.

The 7090/SiCp composite, after being cut into a plate with dimensions of 510 × 337 × 200 mm, was used to investigate the microstructures' and mechanical properties' behavior during sequential motion compaction process. By calculation, we can see that a minimum of 69.36 t device is needed to density the composite for sequential motion compaction process, more less than regular forging process, which need a minimum of 350 t device. Thus we performed the experiment with a 315 t device. A schematic diagram of sequential motion compaction process is shown in Fig. 2. The gap size between the sample and the die was in length and width directions and were 10 mm. The samples were preheated at 723 K for 3 h.

The samples taken from the as-spray-deposited and compaction processed composites were solution treated at 470 °C for 1 h, then quickly heated to 490 °C for 1 h, followed by water quenching, artificial ageing at 120 °C for 28 h.

Table 1 Primary processing parameters

Atomization gas	N_2
Atomization pressure (MPa)	0.7–0.8
Deposition distance (mm)	200–250
Pouring temperature (K)	1173–1193
Diameter of melt stream (mm)	3.4

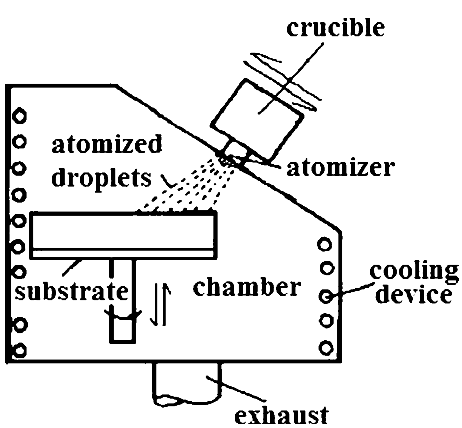

Fig. 1 Schematic diagram of crucible movable spray deposition device for cylindrical billets preparation

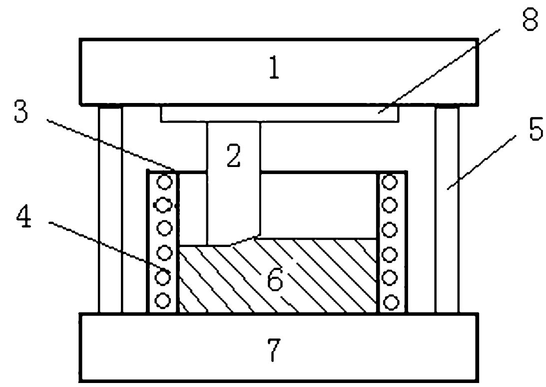

Fig. 2 Schematic diagram of sequential motion compaction: 1, hydrostatic machine; 2, punch; 3, die; 4, electrical bar; 5, caging device; 6, preform; 7, backup plate; 8, guide rail

The microstructure of the 7090/SiCp composite in the as-spray-deposited, as-pressed states was characterized using optical microscope (OM) and scanning electron microscopy (SEM). A JSM-6700F SEM working was used to observe the fracture surface of failed tensile samples. The room temperature tensile tests were conducted with a WDW-E200 Instron tensile testing machine.

Results and discussion

Densification

Figure 3 shows the relative densities at different stages, ε_h = 27.5 and 40.0%, respectively. The relative density is defined as the ratio of apparent density to theoretical density. It is obvious that when the thickness is reduced to 27.5%, the relative densities decrease gradually from near the top to the bottom. There are two stages during the compaction process of the spray-deposited composite: densification and plastic deforming. At the first stage, the pores were elongated and closed at the jointed effect of huge hydrostatic pressure and shearing stress.

Since the deforming force has to overcome not only the friction between the die and the sample but also the inner friction of the composite, this force reduces with the distance far from the punch and influences the densification of the composite [11], which leads to higher density near the top layer than that at the bottom layer. Thus, subsequent sequential motion compaction has been implemented by putting the sample reversely. The results show that relative densities approach the theoretical density when thickness reduction is 40.0%, and they become equal along the height direction, as indicated in Fig. 3.

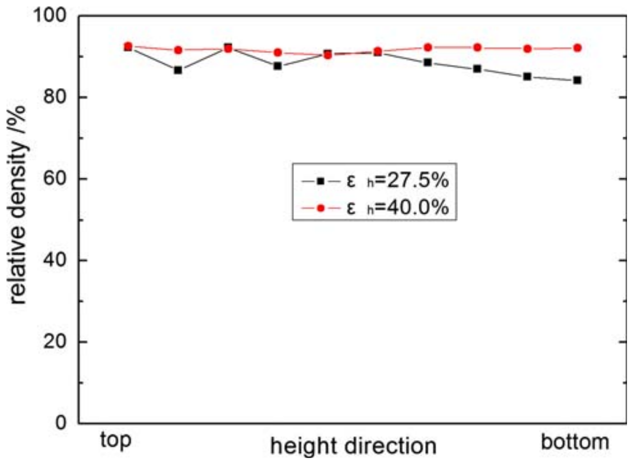

Fig. 3 Relative density across the work-piece thickness of porous work-pieces (thickness reduction is defined as $\varepsilon_h = ((H - h)/H) \times 100\%$)

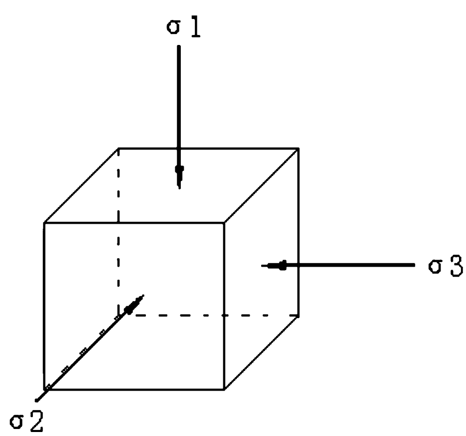

Fig. 4 Stress during sequential motion compaction

Figure 4 shows the model of stress during sequential motion compaction. Based on extensive investigations of the porous materials, Ward and Kuhn [12] demonstrated that the yield equation was well represented by the following relation:

$$f = \left[\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2} + (1 - 2v_p)(\sigma_1\sigma_2 + \sigma_2\sigma_3 + \sigma_3\sigma_1)\right]^{1/2} \quad (1)$$

where f is the yield equation, σ_1, σ_2, σ_3 are the average main stress in three directions, respectively.

Then we can obtain the following relations:

$$d\varepsilon_1 = \frac{d\lambda}{f}\left[\sigma_1 - v_p(\sigma_2 + \sigma_3)\right] \quad (2)$$

$$d\varepsilon_2 = \frac{d\lambda}{f}\left[\sigma_2 - v_p(\sigma_3 + \sigma_1)\right] \quad (3)$$

$$d\varepsilon_3 = \frac{d\lambda}{f}\left[\sigma_3 - v_p(\sigma_1 + \sigma_2)\right] \quad (4)$$

where $d\varepsilon_1$, $d\varepsilon_2$, $d\varepsilon_3$ represent the addition of strain along giving directions, $d\lambda$ is a positive instant proportionality coefficient depending on the total strain; and $d\lambda = \frac{3}{2}\frac{d\varepsilon}{\sigma}$, where $d\varepsilon$ is the addition of effective strain, σ is the effective stress, v_p represents the Poisson's ratio of the porous composite investigated in this work, and $v_p = \frac{1}{2}\rho^n$.

During the compaction process, there was free transverse movement in one direction, so the compressing stress on the composite in which direction is very small, then we can denote $\sigma_3 = 0$; at the same time, if there are few transverse movement in another direction, then we can denote $d\varepsilon_2 = 0$.

According to Eq. 3, we can obtain:

$$\sigma_2 = v_p(\sigma_1 + \sigma_2) = v_p\sigma_1 \quad (5)$$

Combining Eqs. 1 and 5, the result becomes:

$$f = \sigma_1(1 - v_p^2)^{1/2} \quad (6)$$

During sequential motion compaction process, the forcing strain is $d\varepsilon_1$, combining Eqs. 2, 4, 5 and $\sigma_3 = 0$:

$$d\varepsilon_3 = -\frac{v_p}{1 - v_p}d\varepsilon_1 \quad (7)$$

Owing to

$$d\varepsilon_1 + d\varepsilon_2 + d\varepsilon_3 + \frac{d\rho}{\rho} = 0 \quad (8)$$

Combining Eqs. 7 and 8:

$$-\frac{d\rho}{\rho} = \frac{1 - 2v_p}{1 - v_p}d\varepsilon_1 \quad (9)$$

for $v = \frac{1}{2}\rho^n$, then:

$$-\frac{d\rho(1 - 0.5\rho^2)}{\rho(1 - \rho^2)} = d\varepsilon_1 \quad (10)$$

So, we can receive finally that

$$\varepsilon_1 = \frac{1}{4}\ln(1 - \rho^2) - \ln\rho \quad (11)$$

Equation 11 is the relation between height direction deformation and relative density of porous composite, ε_1 is thickness reduction rate.

According to Eq. 11, we can calculate the relative theoretical density is about 93% when the thickness reduction rate is 40%, while the actual relative density is 91.76%.

Microstructure

The microstructural evolution during sequential motion compaction is shown in Fig. 5. Although spray deposition

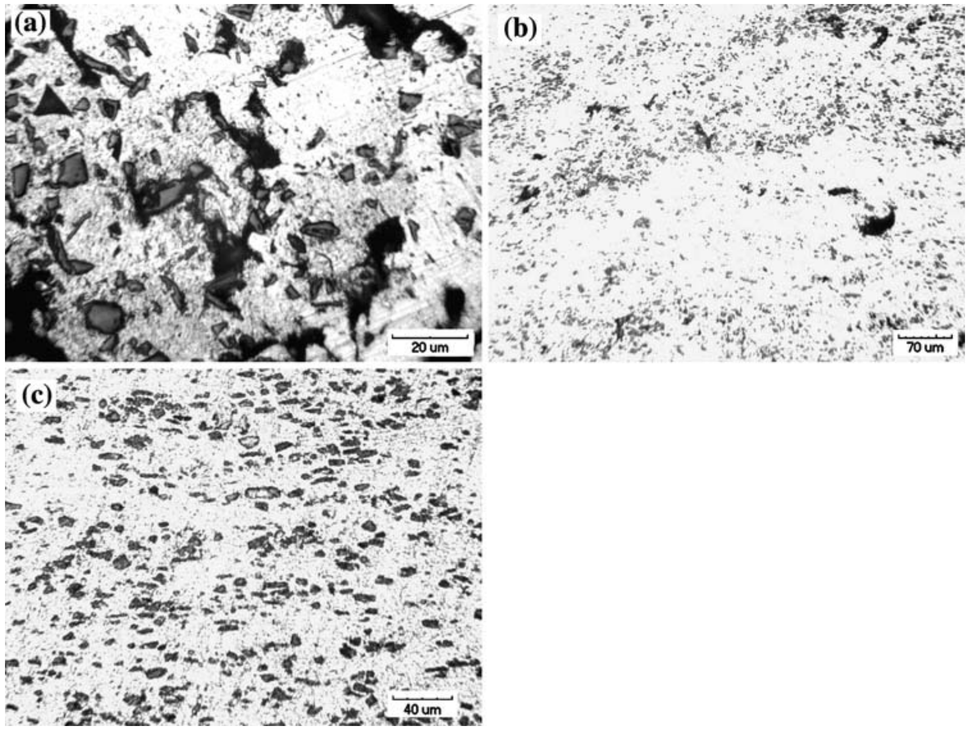

Fig. 5 Microstructural evolution of the preform during sequential motion compaction (**a**) as-deposition; (**b**) deformation for 27.5%; (**c**) deformation for 40%

technology has many advantages over traditional casting and some other techniques for affording large dimension performs without inner stress and composition segregation, but still there are many pores with different sizes and shapes, and SiC particles distributing irregularly in the alloy matrix (Fig. 5a). During the compaction process, with the effect of huge pressing force, the large pores in local regions collapsed into numerous smaller ones gradually. While the thickness reduction rate arrived at about 40%, all the pores had almost vanished and SiC particles distribute uniformly in the matrix (Fig. 5b).

The sequential motion compaction technology is a novel process for densification of porous materials. In this process, the composite mainly has transverse and longitudinal deformation. Since the punch has a relatively small crossing area compared to the traditional techniques, so we only need a small machine but can achieve a large force without destroying the composite. Per step the punch moved a few distance along the transverse and longitudinal directions. By accumulating the small thickness reduction per pass we can achieve large deformation for performs with large dimensions and difficult to deform.

There is a small gap between the die and composite perform in this investigation, thus allowing the transverse flow of the composite in a small range. The shear stress forming in the process of compaction can accelerate the collapse of pores and break the oxide layers on the deposited particles and the metallurgical bonding of surfaces between the deposited particles (Fig. 6). Since the

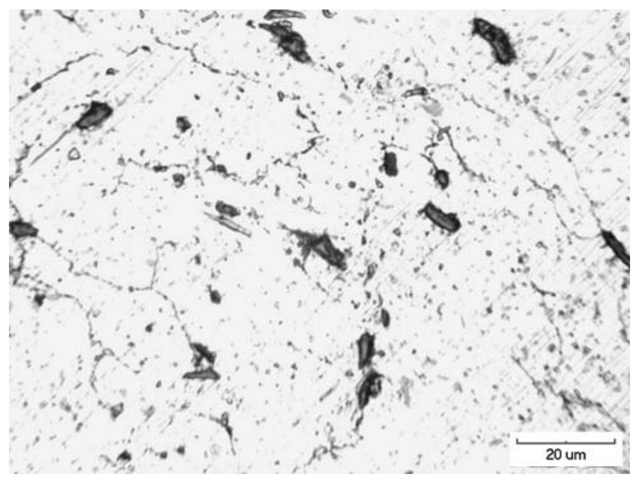

Fig. 6 Changing of pores and interfaces between the deposited droplets in the composite

walls of the die would hinder the transverse deformation of the composite, densification of porous metal occurs under a generalized stress field including both hydrostatic and deviator components, in favor of the densification of the porous metal without inner stress and cracks formed [13].

Mechanical properties

The tensile properties of the spray-deposited and as-pressed materials are summarized in Table 2. From this table, a comparison between the heat-treated spray-deposited and

Table 2 Tensile properties of the spray-deposited and the compaction processed composite materials

State	σ_b (MPa)	$\sigma_{0.2}$ (MPa)	δ (%)
After compaction processed			
Transverse direction	540	519	2.0
Longitudinal direction	325	295	0.5
As-spray deposited			
Transverse direction	154	107	0.4
Longitudinal direction	114	79	0.18

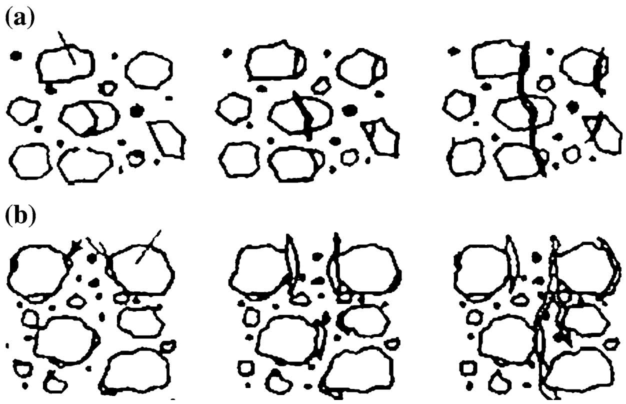

Fig. 7 Fracture model of Al/SiCp composites (**a**) Fracture model of SiC particle (**b**) Separation model of Al/SiCp interface

compaction processed composites shows that this compaction process leads to a substantial improvement of the tensile properties at ambient temperature. Since the improving degree of elongation is very small, mainly brittle fracture occurs.

The low elongation of the composite can be explained by the fracture models shown in Fig. 6 [14]. Figure 7 shows the fracture surface of the as-aged samples. It is clear that cracks form both at the interface between the SiC particles and at the broken SiC particles. Actually, these models are not individual, they are connected with each other. In the first model shown in Fig. 6, when the shear stress acted on the SiC particles arrive the ultimate, they will fracture and become the source of cracks. In the separation model shown in Fig. 6, due to the effect of shear stress on the interface of matrix/reinforced particle, the cracks will appear at the weak interface and will extend when the stress increases.

The SiC particles exert influence on the mechanical properties of the composites by two ways, direct and indirect mechanisms [15]. For the direct mechanism, the particles bear part of the load exerted on the composites when the load is transferred from the matrix with shear action of the boundary, especially when the size of SiC particles is larger than 20 μm. For the indirect mechanism, the particles affect the microstructure of the composites in two aspects. On the one hand, the SiC particles can refine the microstructure. On the other hand, the tangling effects of dislocations around the particles may also result in an increase of the strength. The decrease of elongation mainly results from the fracture of SiC particles and microcracks form along the interface between the SiC particles and the matrix (see Fig. 8).

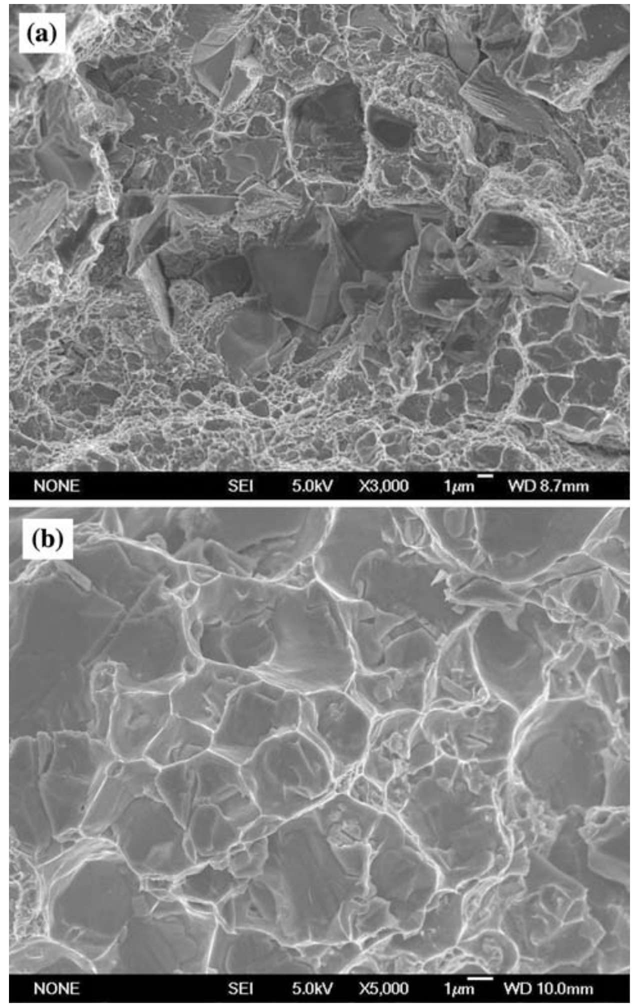

Fig. 8 SEM of the tensile fracture surface of the composite (**a**) as-deposition; (**b**) deformation for 40%

Conclusion

1. The sequential motion compaction technology is a novel process to dense spray-deposited performs, improve the workability and tensile properties and density of porous composite effectively, especially large dimensions and difficult to plastic deform. During the compaction process, the pores in porous composite vanished gradually and achieve metallurgical bonding. So this technology has many advantages over many conventional processing.

2. The ambient tensile strengths of the as-spray deposited, as-compaction processed after heat-treated in transverse and longitudinal directions are 154.58, 114.16, 540.89, and 325.27 MPa, respectively, with the elongations of 0.4, 0.18, 2.0, and 0.5%, respectively. The low elongation is attributed to the fracture of the SiC particles and the interface between the SiC particles and alloy matrix.

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