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Processing, Microstructure, and Mechanical Properties of Large Spray-Deposited Hypoeutectic Al-Si Alloy Tubular Preform

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In this study, a large-scale hypoeutectic Al-Si alloy tubular preform was synthesized by spray-deposition technique and then subjected to a densification processing, wedge pressing (WP). Microstructure and mechanical properties of the as-sprayed and as-secondary processed tube were investigated. The experimental results show that the spray-deposited preform is a coalesced bulk consisting of atomized particles, porosity, and matrix alloy with modified microstructure. The mechanical properties of the porous spray deposits can be substantially improved after WP and subsequent heat treatment due to effective densification and improvements of microstructure.

Keywords Al-Si alloy, densification, large-scale tube, spray deposition, wedge pressing

1. Introduction

As an advanced material fabricating technology, spray deposition has been used to prepare a variety of materials with enhanced properties and performance (Ref 1-3). This technique has been fascinating due to its capability of producing large-scale, near-net-shaped products in single step with inherent rapid solidification effects. Al-Si alloys are widely used for automotive and aerospace applications due to their good castability, wear resistance, higher strength-to-weight ratios, and lower thermal expansion coefficient. However, coarse Si phase and intermetallics in conventional cast Al-Si alloys usually lead to poor mechanical properties and formability due to a low cooling rate during preparation. Previous studies (Ref 4-8) indicated that the shape, size, and distribution of Si and intermetallics in Al-Si alloys can be substantially improved owing to rapid solidification during spray deposition. Thus, the enhanced mechanical properties are expected to be obtained. However, the relatively inferior mechanical properties of the as-deposited preforms are not suitable for structural applications, which result from a small amount of residual porosity and low bonding strength between the as-deposited layers.

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On the other hand, limitations of capacity tonnage or materials formability make it very difficult to process a large-scale spray-deposited tube by traditional techniques such as extrusion or shear spinning. Fabricating such components via spray deposition and looking for suitable methods to densify them are of practical importance for promoting the development and industrialization of this technology. Wedge pressing (WP or cyclic pressing) was first applied in powder compaction, by which metal powder was compacted into dense strip (Ref 9). The fundamental principle of this method was accumulating local small deformation as to integral forming, and our earlier works (Ref 10, 11) revealed that this method, when applied in densification of porous spray-deposited rings and square preforms, was also feasible and cost-effective (especially for large-sized parts). In this study, an oversize Al-Si alloy tubular preform was prepared by multilayer spray deposition (MLSD) technology (Ref 2), and then it is compacted on a press with a capacity of 6300 kN. Results in regard to preparing, secondary processing, microstructures, and mechanical properties of the spray-deposited tube are given.

2. Experimental Details

2.1 Preparation of Tubular Preform

The schematic diagram of spray-deposition process and the photo of the tubular preform obtained are shown in Fig. 1 and 2, respectively.

The nominal composition of the Al-Si alloy was 7 wt.%Si, 0.4 wt.%Mg, 0.1 wt.%Cu, 0.05 wt.%Mn, and balance aluminum, which is similar to that of A356 alloy; therefore, it will be referred to hereinafter as alloy A356. The cast aluminum substrate was preheated to ~350 °C by a built-in electrical resistance furnace to prevent the sprayed preform from cracking/bulking during spray deposition. The dimension of the tubular preform was $\varnothing_{outer}$ 810 mm × $\varnothing_{inner}$ 750 mm × 540 mm and the major process parameters of the spray-deposition experiments are given in Table 1.

2.2 Densification of the Tubular Preform

The preform obtained was machined into several tubes with the sizes of $\varnothing_{outer}$ 802 mm × $\varnothing_{inner}$ 772 mm × 120 mm for the subsequent WP process at ~410 °C, which is schematically shown in Fig. 3. The final total reduction in thickness was ~56%.

The spray-deposited preform was set on steel mandrel which was supported at both ends by two saddle supports. The workpiece was heated inside and outside by a set of heating devices, and the saddle supports were placed on an operating platform. Set on a hydraulic press, the wedge-shaped punch with an angle of 5°-6° between the flat pressing surface and the prepressing one gives rise to a useful predeformed region during compaction. The processing procedure is described as follows: the workpiece together with mandrel remains stationary when the punch goes down and compacts the workpiece, then the punch is lifted up, and the workpiece is turned with a small angle to the next position for another pressing. The steps mentioned above were repeated until the necessary deformation degree of the workpiece was achieved. The pass reduction was about 10%, which can be precisely controlled by a caging device. On the other hand, temperature should be controlled to prevent the workpiece from cracking. The outstanding advantage of WP is that no large tonnage specialized equipment is required when processing a large-sized workpiece.

2.3 Materials Characterization and Testing

Specimens were cut from the as-sprayed and as-compacted tube for the microstructure analysis using optical microscopy (OM) and scanning electron microscopy (SEM). Specimens from the as-pressed tube (reduction ~56%) were heat-treated (solutionizing at 538 °C for 3 h followed by water quenching, aging at 160 °C for 10 h). The density was measured according

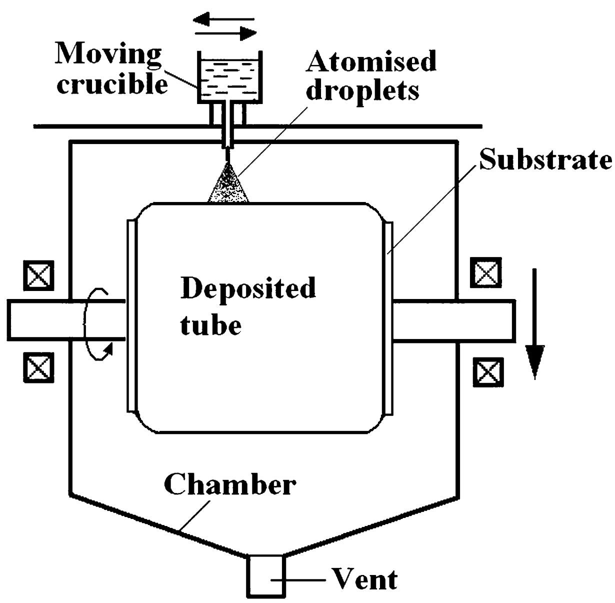

Fig. 1 Schematic diagram of multilayer spray-deposition process

Fig. 2 Photo of the spray-deposited preform

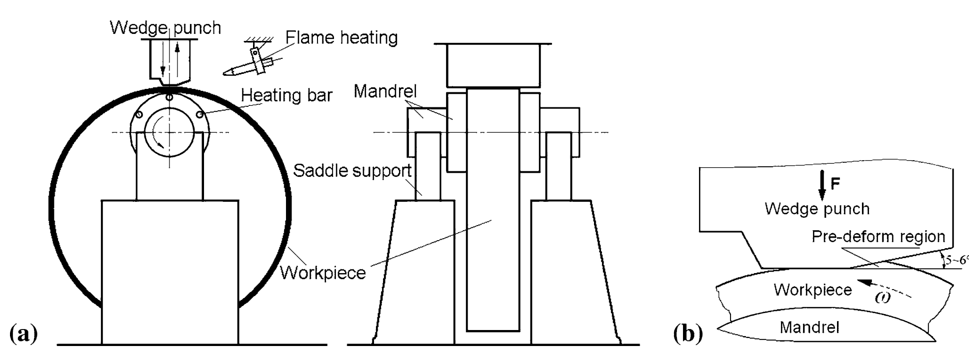

Fig. 3 (a) Schematic diagrams of the tube wedge pressing set-up and (b) the fundamental of wedge pressing

Table 1 Process parameters of multilayer spray deposition of A356 tubular preform

Atomization temperature, °C	Spray pressure, MPa	Spray height, mm	Diameter of melt stream, mm	Scanning period, s	Rotate speed of substrate, r min^{-1}
1000-1020	0.7-0.8	200-240	3.2-3.4	30-60	20-60

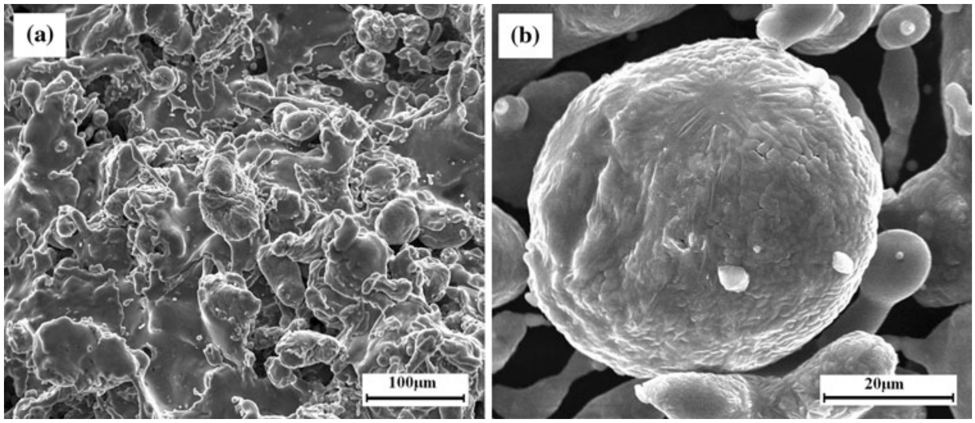

Fig. 4 (a) The deposition surface of the preform and (b) the over-sprayed powder particles with cellular dendritic structure

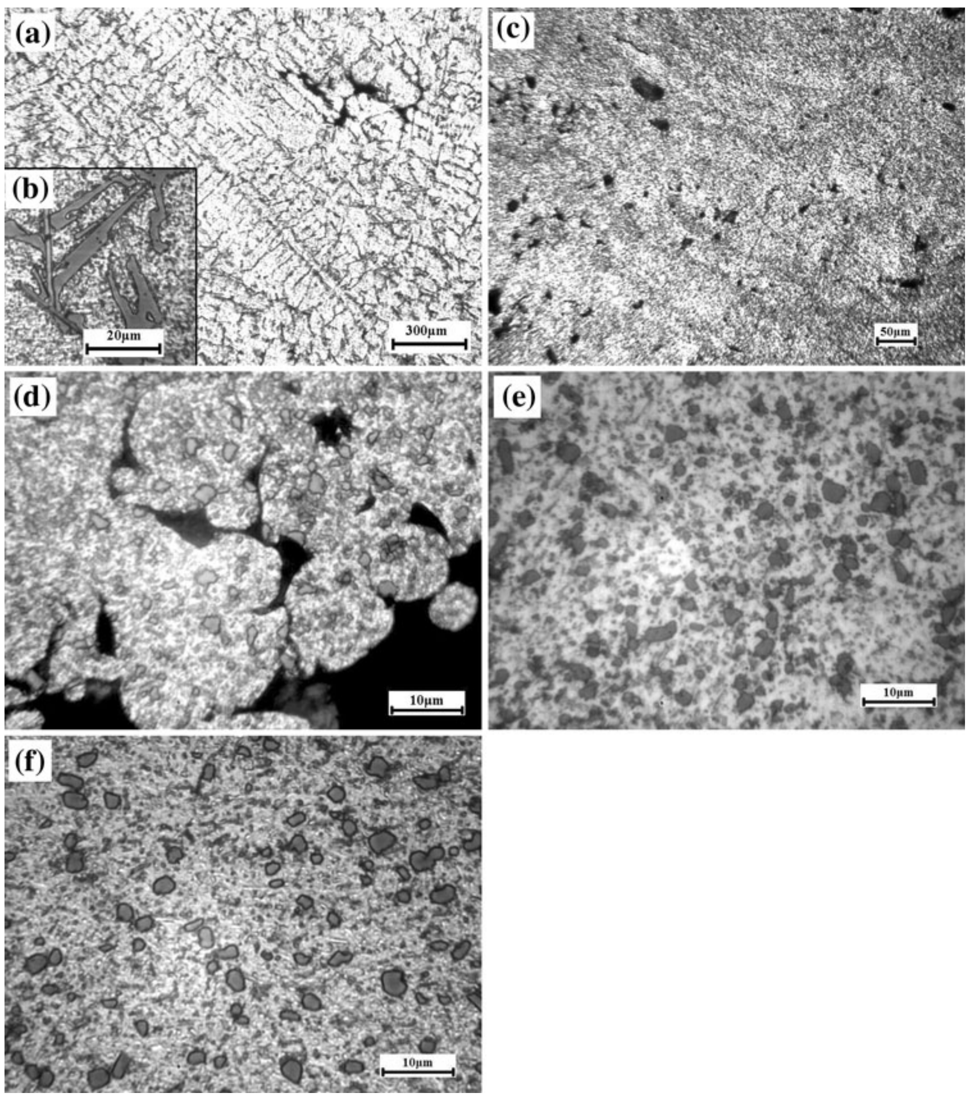

Fig. 5 (a, b) Microstructure in (a) the as-cast materials, (b) high magnification of (a), (c) overview of porosity in the deposits, (d) microstructures in the as-sprayed materials, (e) microstructures in the as-wedge pressed materials, and (f) microstructures in the as-wedge pressed + heat-treated materials

to Archimedes' principle, and the measured density of rolled sheet was taken as the theoretical density. Tensile tests at ambient temperature were conducted on an Instron machine at an initial strain rate of 3.3×10^{-4} s^{-1}, and an average of five measurements was adopted to represent the mechanical properties for each state.

3. Results and Discussion

3.1 Microstructure

The representative microstructure of the tube surface is shown in Fig. 4(a), which exhibits the atomized particles impinging, splashing, remelting, and plastic deforming at the mushy deposition surface. When impacting the deposition surface at a high velocity, they are crushed, but a part of the presolidified droplets may keep a spherical-like shape. The mean size of the particles is about 50 μm. The over-sprayed powder particles display a cellular dendritic structure, as shown in Fig. 4(b), from which the cooling rate of droplets (10^3-10^5 K/s) can be estimated according to the relationship of dendrite arm spacing (DAS) to cooling rate as per the following empirical equation (Ref 12, 13):

$$d = a\,(Q_{avg})^{-n}, \quad \text{(Eq 1)}$$

where d is secondary DAS (in μm), Q_{avg} is average cooling rate (K/s), a and n are material-dependent constants (a = 45, n = 0.25 for A356).

Figure 5 shows the microstructure of the deposits under different conditions and the as-cast materials with the same composition for comparison (Fig. 5a, b).

Coarse needle-like Si together with large α-Al dendrites appear in the as-cast materials while Si particles in the deposits exhibit fine equiaxed morphology. Modification of silicon phase in spray-formed Al-Si alloy is usually associated with copious nucleation, deformation and fragmentation, and remelting mechanisms (Ref 14-16). Another characteristic of the deposits is the presence of a finite amount of interconnected pores, which is caused by entrapped gas, solidification shrinkage, and particles stacking (interstitial porosity) during spray-deposition processing (Ref 1, 2, 16, 17). The main mechanism of the porosity formation could be the interstitial porosity, as shown in Fig. 5(c, d). The initial relative density of the as-sprayed preform is ~88%. However, few pores are observed in the compacted tube (Fig. 5e and f) after multi-pass WP and the boundaries between deposited particles almost disappear due to the plastic shearing deformation, resulting from the metal flow during compaction. No significant difference is observed in the microstructural features such as the aspect ratio of the silicon particles or distribution/size of the intermetallics except that the Si particulates in the as-heat-treated sample appear somewhat coarser and more rounded as a result of thermal treatment.

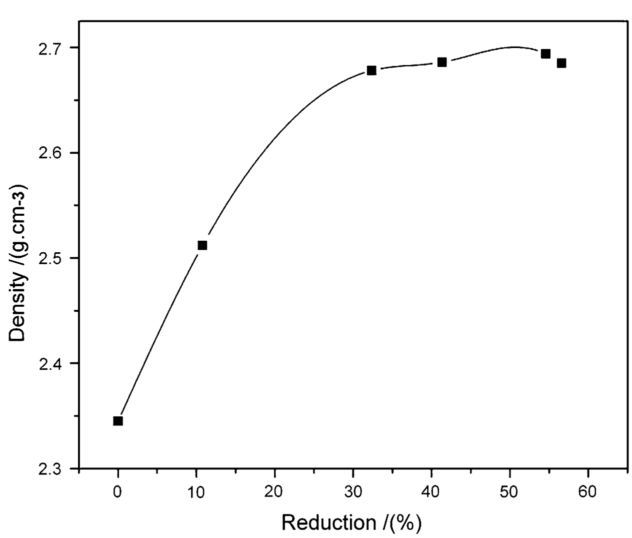

Fig. 6 Densification during wedge pressing

3.2 Densification During Wedge Pressing

As the deposited preform is a coalesced bulk consisting of matrix, the atomized particles and porosity, pores, and primary particle boundaries (PPB) in deposits must be eliminated as possible before the spray-deposited materials are put into use. The densification process during tube WP is shown in Fig. 6.

The high densification rate at early stage of compaction can be ascribed to the larger interstitial pores caving in under applied force at the first stage. The relative densities approach ~98% of the theoretical density when thickness reduction is 33%. Along with the densification process, pores are elongated and closed at the jointed effect of hydrostatic pressure and shearing stress, causing the densification rate slows down.

The photos of spray-deposited tubular preform before and during WP are shown in Fig. 7(a) and (b), respectively. It can be seen that no cracks occur on both inner and outer surfaces during WP.

3.3 Mechanical Properties and Fracture Behavior

Room temperature tensile properties of the spray-deposited A356 alloy tube at different states are shown in Fig. 8.

Evidently, the mechanical properties of the as-spray-deposited preform are not desirable. The microstructure and

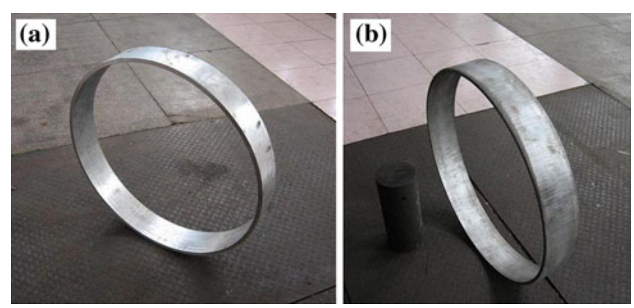

Fig. 7 The spray-deposited tubular preform (a) before and (b) during wedge pressing

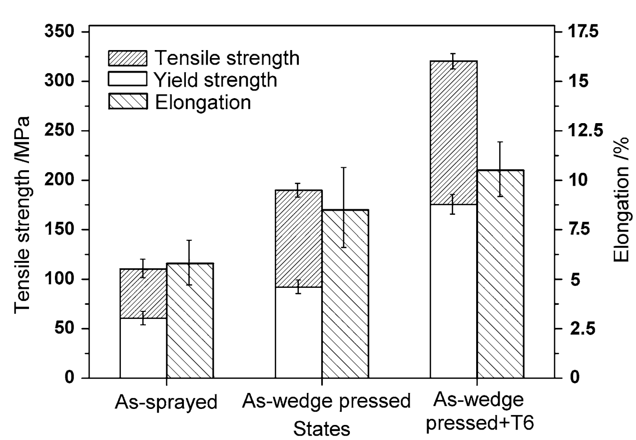

Fig. 8 Mechanical properties of the spray-deposited A356 tubular preform

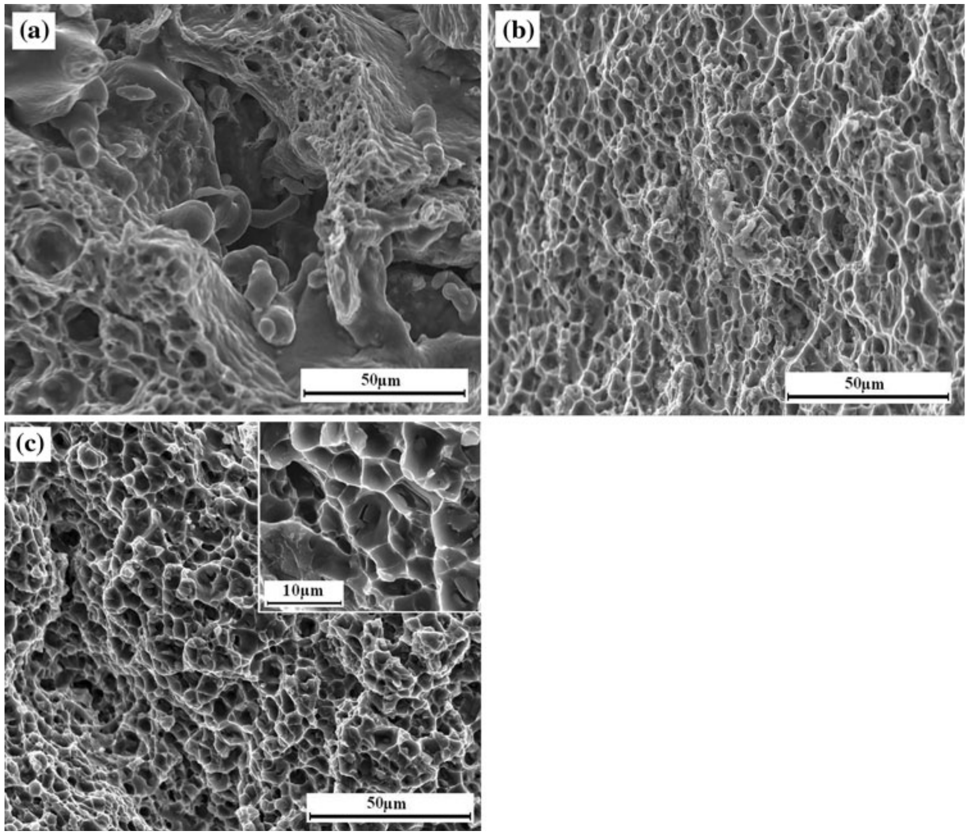

Fig. 9 (a) Tensile fractography of the as-sprayed materials, (b) tensile fractography of the wedge-pressed materials, and (c) tensile fractography of the wedge-pressed + heat-treated materials

the fracture morphology (Fig. 9a) of the porous preform can be used to rationalize the inferior mechanical properties. Cavities and original particle interfaces serve as pre-existing crack sources. The microcracks are prone to propagating rapidly along these defects due to the local stress concentration. Consequently, the low ductility and strength of the as-deposited alloy can be ascribed to the porosity and the weak interface bonding strength between the particles. Pores are effectively minimized/eliminated after densification and plastic deformation during WP together with subsequent heat treatment, and the mechanical properties are significantly enhanced as a result of densification, strain-strengthening, age-hardening, and morphology improvement of the second phases (Si). The fractographs of the wedge-pressed (Fig. 9b) and heat-treated (Fig. 9c) samples are characterized by a large amount of equiaxed dimples, and the cracked Si particles can be observed at the bottom of dimples. This suggests that the uniformly distributed and fine equiaxed Si particles may be beneficial to improve the tensile strength by severing as reinforcing particulates in composites (Ref 18).

4. Conclusions

Large dimension hypoeutectic Al-Si alloy tubular preform was successfully synthesized by spray-deposition technology with modified microstructure. The uniformly distributed and fine equiaxed Si morphologies are resulting from high cooling rate during spray deposition. The substantially enhanced mechanical properties of the compacted and heat-treated materials are attributed to densification, the modified microstructure, age-hardening, and the fine equiaxial Si particles severing as reinforcing particulates in composites. The results also indicate that WP is feasible to process the large porous tubular part on a smaller tonnage press, and it is expected to be applied to process those porous parts in traditional casting and powder metallurgy fields.

Acknowledgments

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