Powder Technology 254 (2014) 12–21

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

Processing and properties of Al-based powder suspension/slurry: A comparison study of aqueous binder systems, stability and film uniformity

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ARTICLE INFO

Article history:
Received 10 October 2013
Received in revised form 16 December 2013
Accepted 30 December 2013
Available online 9 January 2014

Keywords:
Al powder
Slurry/suspension
Aqueous binder system
Coating
Film uniformity
Contact angle

ABSTRACT

A comparative study on the influence of different binder systems was carried out on the processing of aluminum (Al) powder aqueous suspensions/slurries. The role of powder/binder contents, vehicles, contact angle and their effects on corresponding applied films were investigated. In this study, Al-based powder and six types of binder systems were used as main materials. The different compositions of powder–binder with three binder contents of 1, 1.5 and 3 wt.% at three levels of powder loading i.e. 35, 45, 55 wt.% (corresponding to 16.7, 23.3 and 31.1 vol.%.) were grinded in a planetary ball mill for 2 h. Then, the rheological behavior and stability of prepared slurries were determined using a viscometer and common sedimentation test method, respectively. Optical and scanning electron microscopy (SEM) was utilized for evaluation of prepared films' microstructure, morphology and uniformity. Also, in order to investigate the dependency of wetting behavior of vehicle to surface quality the contact angle of used vehicles on the Al surface was measured via Sessile Drop method. It was found that using different binder systems a variety of slurries and final film properties were obtained. It was obviously indicated that the type and amount of binders, powder loading and wetting behavior of binders (contact angle) are the most important parameters affecting the slurries' stability and film smoothness. Increasing solid loading, in a given binder content, leads to a decrease in the stability and rise in viscosity of slurries. The mutual dependency of binder content and contact angle of different binders ranged 15.64–50.17° affect film's surface quality. Polyethylene glycol/carboxy methyl cellulose (PEG/CMC) system with the lowest contact angle of 15.64° showed appropriate slurry's stability and film uniformity in all ranges of studied binder systems. The sample contained 3 wt.% PEG/CMC binder (corresponding to 21.81 vol.% in final film composition) and 35 wt.% solid loading (corresponding to 78.69 vol.% in final film composition) revealed the best slurry stability and final film quality.

1. Introduction

A superior combination of appropriate mechanical and physical properties makes aluminum, its alloys and composites attractive for a wide spectrum of applications. These properties include high specific strength, elastic modulus, stiffness, good wear resistance, light weight, good electrical and thermal conductivity and excellent corrosion resistance. Aerospace, automotive, military, electronics and aircraft industries are some potential areas applications of these advanced materials [1–7].

Powder metallurgy technique as a near net shape manufacturing process offers the exceptional properties of Al parts; in which the cost effective parts produced with minimum finishing/post operations. Because of aforementioned appropriate properties, Al-based coatings or layers can be used potentially as an alternative coating instead of hazardous materials such as Cd in strategic aerospace industries [7]. Besides, there is a possibility for producing a uniform tailored shell structure of Al as a cellular/porous body (foam). These components can provide the most requirements of foams such as lightness, high specific strength, especially uniform deformation and predictability of properties [8–10]. Several deposition methods such as electroplating [11], physical vapor deposition [12], and chemical vapor deposition [13] can be used for producing an Al coating; but they are so expensive and have some limitations. Application of Al coating via slurry process is easy, low cost and flexible method which can be used on sacrificial or permanent substrate by means of brush, immersion or spray coating [7]. The slurry based coating process offers the possibility of producing coating with various chemical compositions (different alloying systems), composite layers and functionally graded materials which can't be reached by other established methods. Also, despite the coating thickness with conventional coating methods don't exceed from 0.05 mm [14,15], the slurry coating allows the coating layers with the thickness of a few microns to several millimeters which the thickness and surface morphology of coating can be controlled by choosing a certain powder particle shape and size [16]. Against, controlling the coating porosity and some sintering and consolidation considerations are the limitations of a slurry based process which require more attention and modifying operational conditions [7].

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http://dx.doi.org/10.1016/j.powtec.2013.12.051

Powder suspension/slurry-based processes are flexible and applicable manufacturing methods among the powder metallurgy techniques to develop advanced components. Tape casting [17–22], spray and dip coating [20,21], slip casting [22,23], infiltration [24], etc.; are several fabrication and forming slurry-based processes in which a slurry consists of a metallic/ceramic powder, solvent, binders and some other additives such as surfactant and dispersant, can be used for creating a porous/dense structures.

Among the solvent and water based suspension/slurry, the aqueous slurries are more attractive from the environmentally friendly point of view. Several researches have been carried out on the processing, characterization and optimization of aqueous ceramic based suspensions/slurries. Some investigated materials and processes are included Gd_2O_3 doped CeO_2 nanoparticles aqueous slurry for tape casting [17], Al_2O_3–Ni for slip casting [20], rheological properties of aqueous Ceria dispersion [25], aqueous Al_2O_3 slurry for spray drying [26] and slip casting [22], Y_2O_3-stabilized ZrO_2 [27], aqueous tape casting of cordierite-based glass ceramic [18]; but there are a few documents related to metal powder-based suspensions/slurry characteristics. LeBeau and Boonyongmaneerat [28] compared the aqueous binder system in producing and characterization of W/Al_2O_3 layers via dip coating. They found that, the use of different binder systems provided powder slurries and green materials with very distinct properties such as stability, surface quality and uniformity.

Developing an appropriate binder having good compatibility with water and attaining desired properties of intermediate and final products are the major factors in a slurry based process. This chosen system should provide required criteria of proper slurry including stability, appropriate viscosity of slurry and sufficient green strength of the as dried products [28]. Likewise, some qualitative aspects such as surface quality and uniformity should be considered. There are some reports about investigation of water-based binder systems such as polyvinyl alcohol (PVA) [27,28], Starch [28], latexes [28,29], carboxy methyl cellulose (CMC), Polyethylene glycol (PEG) [22,26] etc.; which mostly have been used for ceramic based slurries and forming processes such as slip casting and tape casting. Tsetsekou et al. [22,26], in two distinct studies, investigated the effect of different dispersants/binders on the rheological behavior and stability of alumina and titania slurries. They found that, there are optimum concentrations for each dispersant to achieve appropriate stability and low viscosity. Also, they noted CMC-based slurries had excellent stability; but the viscosity was significantly increased. LeBeau and Boonyongmaneerat [28], examined styrene butadiene latex, PVA and starch binders for preparing W/Al_2O_3 slurries and layers. They found that, the latex based slurry and its corresponding film has excellent properties. The slurry with PVA binder had poor stability; but its prepared layer revealed excellent surface quality. Starch based slurry exhibited a reverse manner in comparison PVA binder.

According to the above statements, a systematic study of aqueous Al-based slurries/suspensions for coating process and the effect of wetting/contact angle have not been reported.

In the present study, some water soluble binders such as PVA, PEG/CMC, and three types of acrylic styrene copolymer latexes were used to prepare the Al based suspensions/slurries. Then the effect of processing parameters on the rheological behaviors, stability and film uniformity of suspension was investigated. Finally, the comparison of several conditions and parameters were conducted. Stabilization mechanism, powder/binder content, binder type, viscosity and contact angle were considered in discussions.

2. Material and methods

2.1. Materials

2.1.1. Powders

Al, Mg and Sn powders with average particle size of 25 μm, 45 μm and 43 μm (measured by Malvern-ZEN 3600, laser particle size analyzer), respectively, were used to prepare powder suspensions/slurries with desired compositions. The characteristics of primary materials were listed in Table 1. The SEM micrographs of Fig. 1 indicate the irregular, plate-like and semi-spherical shapes of Al, Mg and Sn, respectively.

2.1.2. Binders

Different water based binder systems and some other necessary additives were used to prepare powders slurries. The specifications of these materials are listed in Table 2. As a binder system, the combination of PEG6000/CMC with mass ratio of 3:1 was used for slurry preparation. For all slurries, in order to improve the dispersion efficiency of Al powder, about 0.03 wt.% VICTAWET-12 was used as a wetting agent. The effect of binder type and its content were investigated on the suspension stability and properties of corresponding films. The general characteristics of binders are given in Table 2. Some specifications of used latex binders are described briefly as follows:

2.1.2.1. Polymer latexes. Copolymers of acrylics and styrene have many specific features such as good film-forming, gloss, transparency, and mechanical properties. Their corresponding products have been widely used as coatings, paints, and adhesives [30]. In this study, three commercial types of acrylic styrene copolymer latexes were used which briefly are introduced as follows:

1. *Simacryl U-96* is an anionic emulsion of acrylic styrene copolymer with very soft film and self cross linking property. The solid content of this binder is about 40 wt.% [31].
2. *Simacryl R-4410* is an anionic emulsion of acrylic styrene copolymer with a clear and stable film and excellent non cross linking properties. The solid content of this binder is about 50 wt.% [31].
3. *Simacryl SH-305* is an anionic emulsion of acrylic styrene copolymer with hard film and self cross linking properties. The solid content of this binder is about 50 wt.% [31].

2.2. Processing

In order to obtain a dense powder structure, minimum required strength of green specimens and to facilitate the post heat treatment (debinding/sintering), the maximum powder loading and hence the minimum binder amounts were used. For this purpose, the solid loadings were applied over of critical powder loading point. The value of critical powder loading or critical powder volume concentration (CPVC) was estimated about 74 vol.% using a procedure similar to the oil absorption method according to ASTM D281, with deionized water [32].

To examine the effect of binder type, binder content and powder loading, 1, 1.5 and 3 wt.% of each binder were used in powder loading of 35, 45 and 55 wt.% (corresponding to 16.7, 23.3, 31.1 vol.% of total suspension), which were over of CPVC. The amount of binders was calculated according to active matter of each binder. The full factorial combinations of the amounts of binders and solid loadings are given in Table 3. The suspensions/slurries with respect to final composition of Al–1Mg–2Sn (wt. %) were prepared using a planetary ball mill. The pre-weighted constituents were added to 250 ml polyethylene vial contained alumina balls (10 mm in diameter). The mixing process was carried out at 200 RPM. To attain maximum homogeneity of slurries, all samples were milled for 2 h with ball to powder weight ratio of 10:1.

For investigation of produced film uniformity from prepared slurries, several films of 200 μm thickness were applied using a film applicator (Doctor Blade) on polystyrene sheets (size of 10 cm × 5 cm × 0.2 cm); then dried for 24 h at room temperature.

2.3. Characterization

2.3.1. Rheological measurements

In order to investigate the rheological and flow behavior, the slurries' viscosities were determined using a rotating spindle viscometer