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Advance on Al_2O_3 Particulates Reinforced Aluminum Metal Matrix Composites (Al-MMCs) Manufactured by the Power Metallurgy(PM) Methods- Improved PM Techniques

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Abstract. Aluminum metal matrix composites (Al-MMCs) with Al_2O_3 particulates as reinforcement fabricated by the power metallurgy (PM) methods have gained much attention due to their unique characteristics of the wide range of Al_2O_3 particles addition, easy-operating process and effectiveness. The improved PM techniques, such as the high energy ball milling, powder extruder and high pressure torsion were applied to further strengthening the properties or/and diminishing the agglomeration of strength particles. The formation of liquid phase assisted densification of compacts to promote the sintering of composites. Complex design of Al_2O_3 particles with other particles was another efficient method to tailor the properties of Al-MMCs.

1. Introduction

Aluminum metal matrix composites (Al-MMCs) are one of the most conventional but very important types of metal matrix composites and have made numerous applications in aerospace, automotive, military, sports and electronic industries due to low density, high toughness, high specific strength, good thermal stability, excellent wear resistance and controllable expansion coefficient[1-4]. There are a few reinforced materials, such as silicon carbide, aluminum oxide, the quasicrystalline phase, graphite, and so on[5-11] in the form of particles or whiskers that can be used for the reinforcement of Al-MMCs because of their improved physical and mechanical properties[3,7]. Among them, Al_2O_3 are characterized by high stable, inert and thermal stability, which make it become one of the most popular reinforcement phases and have gained much attentions[3,6,8].

In general, Al-MMCs are fabricated using liquid phase, liquid-solid, and solid state processes. Among them, the solid state process or powder metallurgy (PM) process is considered as a good technique in production of Al-MMCs. The outstanding characteristics of the PM method is the lower processing temperature and more effective in terms of particle distribution, than the casting methods in which the melting temperature always are demanded. Another advantage of the PM technique is its ability to manufacture near net

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shape products at low cost [12-13]. Moreover, it is possible to achieve composite materials production with wide range addition of reinforcement particles by the PM method, and even to obtain production which cannot be obtained by any other alternative method[6].

There are many factors affecting the properties of Al-MMCs, such as the particle content and size, particle size distribution of Al_2O_3 powders, dispersion of reinforcement particles in the matrix, the mixing procedures, compaction types and pressure, sintering methods and process parameters [13]. However, the properties and the basic characteristics of composites are thought to be controlled by the mixing methods and sintering process. In the PM processes, the mixing process is the critical step towards a homogeneous distribution throughout the consolidated composite material [14-16]. The agglomeration and segregation of the particles undoubtedly deteriorate the mechanical properties of composites. It has been one of the most main research orientations to diminish the agglomeration and segregation of particles, even in the PM method. Great progress has been made in recent decades on the improved PM techniques to decrease the agglomeration of Al_2O_3 particles. Meanwhile, many of those techniques have also obtained to further improve the mechanical properties of Al-MMCs. In this paper, the evolvement on the improved PM techniques is reviewed in Al_2O_3 particles-reinforced Al-MMCs.

2. Improved PM Techniques

Although all relative processes in conventional PM techniques including the mixing process, sintering process, annealing process are necessary steps to form the consolidated composite material, some complementary processes, such as powder extrusion, forging, hot-rolling, and so on, can help to optimize the microstructure and mechanical properties [13-15].

Hot Rolling Process. Zabihi et al. [16,17] had successfully produced the Al-MMCs strip with 2 wt% and 4 wt% Al_2O_3 by PM techniques, in which the hot-rolling process was adopted, after the milling and vacuum hot pressing. The hot rolling process improved the uniform distribution of alumina particles in Al matrix and the bonding of Al and Al_2O_3. The hot-rolled composites demonstrated that the failure mode in the hot-rolled Al-2 wt% Al_2O_3 composite strips was a typical ductile fracture, while the failure mode was shear ductile fracture with more flat surfaces in Al-4 wt% Al_2O_3 strips.

Powder Forging Process. The powder forging process was adopted between the cold pressing and sintering process to consolidate the cold compacts by Luangvaranunt et al [18] in an Al-Al_2O_3 composite by PM techniques. The cold compact was heated to 600°C for 15 min, then was immediately taken out of the furnace and forged at 660 MPa. The final deformation of sample was Ø35 mm from Ø30 mm before forging. A high relative density of 98-99% was obtained in the forged billets before the sintering. Tensile strength and ductility reaches 120 MPa and 8%, respectively, for specimen forged and annealed at 600°C for 30 h, which were higher than them of pure Al billets at the same processes.

The effects of powder forging were also studied by Balog et al[19]. The powder was cold isostatically pressed at 200 MPa. And then the obtained preforms were compacted by forging, in which they were performed using a spindle press at 450°C, 90 kJ of press energy and a maximal speed of 550 $mm \cdot s^{-1}$. Forging with limited amount of induced shear led to isotropic microstructures of polyhedral grains. The microstructure consisted of Al single grains reinforced with continuous 3D oxide skeleton. It was due to the stability of 3D skeleton that the composites showed superior thermal stability and retained their microstructures after 336 h annealing up to 450°C. The tensile strength of 138 MPa of composites by forging at 500°C was obtained, which was far superior to any conventional Al alloy.

High-Energy Ball Milling (HEBM). HEBM is the most commonly used method to mix and disperse the powder in the PW technology, which is also called mechanical alloying or mechanical milling. It was first developed by Benjamin [20] to produce nickel- and iron-based superalloys hardened by oxide dispersion, involving repeated deformation, welding and fracture.

Prabhu et al [21] have successfully prepared a Al-Al_2O_3 powders with uniform distribution of the Al_2O_3 reinforcement by HEBM techniques, in which the volume content is as high as 50% and particle size is as small as 50 nm. This was, for the first time, reported a uniform distribution of such ultra-fine particles of 50 vol% Al_2O_3 in an aluminum matrix.

The effects of HEBM on the structural evolution of Al_2O_3 reinforced Al-MMCs were studied in detail[22-24]. The aluminum peaks tended to broaden as the milling time increased, indicating a decrease in the crystallite size[23]. And accumulation of lattice strain was also identified by the X-ray diffraction pattern of the milled powders [25]. It was observed that the crystallite size of the aluminum matrix was decreased to about 45 nm from a mesh size of -100 μm, and the lattice strain was increased to over 0.1%[23]. Meanwhile, the morphology changed from spherical shape→irregular particles→almost equiaxed particles with the milling time. However, no subsequent phase change was observed even after 20 h of milling [26].

It was reported that the addition of Al_2O_3 particles accelerated the milling process of Al powder because the small hard particles might act as milling agent [23,27]. The morphology also changed from flake-like to equiaxed shape, which occurred earlier compared to unenforced Al powder. Also with the profoundly decrease of size of the matrix particle, the hardness and strength were significantly increased compared to the monolithic aluminum. The size distribution of the composite particles compared to the Al powder was changed [27-30].

It was observed that most of the reinforcement particles had dispersed inside the matrix powder rather than smeared on the surfaces of Al particles after milling [29,31]. With the increase of milling time, the ductility of composites was also improved by the uniform distribution of Al_2O_3 particles, which would increase the elongation [30]. It is also proved from the fracture surface of composite. The milled powder showed a gross plastic deformation with large interlocking. Whereas only localized deformation in the contact zones between the particles occurred in the powder without milling.

However, the milling process significantly decreased the densification of the Al-Al_2O_3 powders, owing to the changes occurred in the hardness and strength [23,30] and the morphology of the Al particles. At the early stage of consolidation, in which the rearrangement of particles was dominant for densification, the density of the without milled powder was higher than that of the milled powder. Only further increasing the compaction pressure, in which densification was mainly induced by plastic deformation of the ductile aluminum particles, the difference between the densities was almost diminished. This could be more effective to anneal the powder at 100°C to release the work hardening resulting from the milling process [31].

Powder Extrusion. The powder extrusion was often adopted in PM technology to help to optimize the reinforcement distribution [13-15,24,32], and to improve the properties[33], although the typical lamellarity is often revealed in the longitudinal section in extruded materials[24]. Another advantage of extrusion process is the possibility of making extruded composite products with high dimensional accuracy.

Strong microstructure in Al-MMCs by disrupting the oxide and hydroxide layers coating Al powder particles was achieved by compaction stress of 74 MPa and hot pressing at temperature of 450°C applied for 4 h, followed by hot extrusion [13]. Al_2O_3 particles were observed to be uniformly distributed throughout the microstructure except for some clusters of particles surrounded by an interface of porous aluminum matrix. The more important was that considerable ductility was obtained in Al_2O_3 particle reinforced Al-MMCs, which was an advantage of this technique over other techniques of MMCs manufacturing. It was confirmed that the main fracture mechanism in Al-Al_2O_3 MMC was the ductile mode of void initiation, growth, and coalescence. Voids initiated at Al-Al_2O_3 inter-facial sites or the porosity retained in the aluminum matrix.

Balog et al [19] also studied roles of the extrusion on the composite with fine-Al powders and its native Al_2O_3 skin. The extrusion was performed at 450°C, using extrusion ratio R = 11:1. The average grain size of 505 nm was calculated after extrusion in the composites cold-isostatically pressed at 200 MPa, which was smaller compared with that sysnated by other processes, such as HIP or forging. Also the tensile strength as high as 310 MPa was achieved at room temperature, because of the grain boundary strengthening mechanism acting in the fine microstructures.

The high-temperature behavior of Al-Al_2O_3 MMCs was studied by Mazen[34], in which, the PM techniques of hot pressing followed by hot extrusion were used. After hot pressed at 600°C using a stress of 150 MPa for 3 h, the compacts were hot extruded at an extrusion ratio of 5:1 to impart densification. For the unreinforced matrix and Al-MMCs containing up to 5 wt% Al_2O_3, dynamic recovery dominated up to 200°C, but for Al-MMCs with 10 wt% Al_2O_3 dynamic recrystallization have started at 200°C. The effects of high temperature on the yield stress and tensile strength were also studied.

Reciprocating Extrusion Process. A reciprocating extrusion process was introduced to consolidate a 6061Al-Al_2O_3 composite [35]. The mixing powders were firstly hot pressed at 300 MPa at temperature of 300°C, and then the billets obtained with a diameter of 40 mm and length of 50 mm were deformed by 30 passes at 460°C through a reciprocating extruder with the extrusion ratio of 9.5:1. The results showed that the fully densification of composites with different Al_2O_3 contents were achieved by an effective kneading effect in the reciprocating extrusion process. And the Al_2O_3 particles were distributed uniformly in the matrix because of the homogenization resulting from kneading. Also those had great roles on the mechanical properties. The composite exhibit excellent ductility, an elongation of 10.6 at a tensile strength of 290 MPa was obtained in the Al-MMCs with 10 wt% Al_2O_3.

High-Pressure Torsion. Recently a high-pressure torsion (HPT) technique was used to produce Al-MMCs. HPT is a processing technique to produce ultrafine grained samples through severe plastic deformation, which makes it possible to consolidate powders to produce a bulk form of metal-ceramic nanocomposites at lower temperatures without sintering process[36]. Ashida et al[37] fabricated Al-MMCs containing 30 vol% Al_2O_3 in the forms of disks and rings, in which a pressure of 6.0 GPa and 3.0 GP was conducted respectively at room temperature with a rotation speed of 1 rpm. The results indicated that the dispersion of Al_2O_3 particles became finer and more uniform with increasing number of turns in the HPT process, although the agglomeration with a maximum size of ~ 30 μm was still visible even after 50 turns in the edge parts. Also it was observed that the hardness kept increasing at any HPT condition in the composites, whereas it was saturated to a constant level of 35 Hv in pure Al. The hardness of the composites increased with increasing distance from the center and with increasing the number of turns in the disk and ring samples. The maximum hardness of 190 Hv was attained in the ring samples and this was higher 60 Hv than that in the disk samples.

3. Liquid Phases Formation

During PM processes, the formation of the liquid phase usually assisted densification of compacts and gave fast sintering for higher diffusion rates associated with liquids compared to solid. Min et al[38] studied the effects of the liquid phase on the sintering in the Al_2O_3-reinforced 2xxx series Al-MMCs. The liquid phase sintering occurred in the composite materials because the eutectic liquid of Al-Cu was formed. The formation of the liquid phase induced the sintering and the sintered density increased due to pore filling. From microstructure, the pores were inhomogeneously distributed throughout the specimen before the liquid phase had not effectively contributed to densification and pore filling at the sintering temperature of 610°C. After the eutectic liquid of Al-Cu was formed at 620°C, liquid phase sintering occurred with increasing holding time and the reduction of pore space could also be seen from microstructure.

It was important to understand the behavior of liquid formation in the Al-MMCs materials using the PM technique. Generally there was no solubility between the liquid and solid, so the densification occurred at the rate associated with sintering the solid skeleton and the liquid is simply a pore filling agent [39,40].The amount of the liquid phase had a significant impact on the sintering trajectory. It seemed that liquid phase infiltrate into space between ceramic agglomerate, the more liquid amount was required to obtain the enhanced sinterability of composite materials [38]. Moreover, in Al_2O_3 particles reinforced Al-MMCs the heat capacity of Al_2O_3 should be considered fully [40,41]. Because the heat capacity of Al_2O_3 was relatively large, heat was concentrated on Al matrix around Al_2O_3 particles in case of composite powder, the fast diffusion of liquid phase would be emerged. So there was no longer persistence of liquid phase during sintering. To achieve persistent liquid phase sintering, the solid and liquid contents should converge to constant values while the pores was annihilated, giving densification[39].

4. Alumina Particles′ Compounds

It had been proved that alumina particles′ compounds could effectively improve the properties of Al-MMCs[7,42-43]. In an Al-based composites reinforced with TiB_2 and Al_2O_3 particulates, the yield strength of 545 MPa and tensile strength of 638 MPa were achieved, which were higher 9 and 6.8 times than that of pure Al. The incorporation of TiB_2 and Al_2O_3 particulates in Al led to a substantial improvement of its endurance limit from 40 to 170 MPa[5]. Abouelmagd[4] discussed that effects of complex design of Al_2O_3 particles with Al_4C_3 on the Al-MMCs in PM technique. The Al-MMCs rods with compound powders (1.5 vol% Al_2O_3+Al_4C_3) were prepared, in which HEBM, cold pressed and followed by hot extrusion at 500°C also used. The results showed that addition of Al_4C_3 induced the homogeneous and increased the dislocation density, which increased both hardness and compressive strength of composites. In the composites with 1.5 vol% Al_2O_3+12 vol% Al_4C_3, the hardness and the compressive strength values of composite were 82 Hv and 750 MPa, which was approximately twice than that of Al-MMCs without Al_4C_3 additions. Moreover, the Al_4C_3 increased the strength of composites in the high temperature. Compared with the composite with only 1.5 vol% Al_2O_3, the highest percentage of improvement was about 150% at 150°C deformation temperature, and was achieved in the Al-MMCs with the additional 12 vol% Al_4C_3.

5. Summary

The advances were reviewed on the improved PM techniques in Al_2O_3 particulates reinforced Al-MMCs. It was seemed that the most important factor in the fabrication of Al-MMCs were the uniformly dispersion of the reinforcements. The HEBM, powder extrusion, HPT, and so on, were adopted to increase the dispersibility of Al_2O_3 particles.

Properly complex design of alumina particles with other powders was proved to further improve the mechanical properties of Al-MMCs. There is still much about Al-MMNCs that is in need of further research. It is worth studying to innovate the PM methods to control the microstructures and to increase the properties of composites at a low cost.

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