Advance on Al$_2$O$_3$ Particulates Reinforced Aluminum Metal Matrix Composites (Al-MMCs) Manufactured by the Power Metallurgy Techniques- Microstructure and Properties

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Abstract. Aluminum metal matrix composites (Al-MMCs) with Al$_2$O$_3$ particulates as reinforcement fabricated by the power metallurgy (PM) techniques have gained much attention due to their unique characteristics, which combine the roles of the process method, Al$_2$O$_3$ particles and aluminum matrix. The contents and sizes, locations and dispersion of Al$_2$O$_3$ particles on the matrix affect the mechanical behaviors and ultimate properties of the composites, which depend on microstructure of the final composites, usually including porosity, the grain size of composites and the dispersion of Al$_2$O$_3$ particle in the matrix. The agglomeration and segregation of the particles deteriorate the mechanical properties of composites.

Introduction

Aluminum and its alloys have gained significant attention as matrix material for Al metal-matrix composites (Al-MMCs) for their low density, high strength, high hardness and high-specific elastic modulus etc. [1-7]. Among them, Al$_2$O$_3$ particulates reinforced Al-MMCs by the powder metallurgy (PM) techniques have been the subject of intensive research in recent years for several reasons [8-12]. First, Al$_2$O$_3$ particles are characterized by high stability, inert and thermal stability, and low-cost effectiveness compared to Al$_2$O$_3$ fibers, making it one of the most popular in the strengthening particles, such as SiC, AlN, BN, and so on [2, 13-15]. Second, the PM methods has been outstandingly developed recently and become one of the most effective and economical methods for manufacturing Al-MMCs, which can diminish the segregation and agglomeration of the reinforcement particles, as well as harmful reactions at the interface[16-18]. Third, the PM techniques are believed to be a more suitable process than other methods for the production of Al-MMCs [19-21]. In fact, it is an challenge to uniformly disperse Al$_2$O$_3$ particulate by other processing route due to the poor wettability of Al$_2$O$_3$ particulate at matrix-reinforcement interface [17, 22], whereas, the segregation effect and intermetallic phase formation can be reduced by the PM process, especially compared with the liquid state processes [23, 24].

The physical and mechanical properties of the Al-MMCs fabricated by PM technique are influenced by the characteristics of both matrix and Al$_2$O$_3$ particles, and by the processing variables. The former mainly involves Al$_2$O$_3$ particle content and its size, particle size distribution of both matrix and Al$_2$O$_3$ powders, and dispersion of reinforcement particles in the matrix, and so on. The latter comprises the mixing procedures, compaction types and pressure, sintering methods and process parameters (temperature, heating rate and time) [25].

Based on the above, there are many factors affecting the properties of Al-MMCs, however, the properties ultimately depend on microstructure of the final composites, usually including porosity, the grain size of composites and the dispersion of Al$_2$O$_3$ particle in the matrix. These 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 key step towards a homogeneous distribution throughout the consolidated composite material [26-28]. 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, and great progress has been made in recent decades. In this paper, the advances referred to above are reviewed on microstructure and typical properties in Al_2O_3 particles-reinforced Al-MMCs developed by PM techniques.

Microstructure

The Al_2O_3 particles content had great influences on microstructure of the Al-MMCs. The addition of alumina particles would impede the grain growth, leading to finer grain structure. Rahimian et al [29] revealed that the grain sizes became smaller with higher alumina concentration in the pure Al matrix reinforced with micron-sized Al_2O_3 particles. However, the clustering was found in the samples with above 10wt% alumina content; even the heterogeneous particle distribution was observed in the samples containing 20wt% alumina. Hesabi et al [30] also observed that the addition of the Al_2O_3 reinforcement particles profoundly decreased the average particle size of the matrix particles. The role of addition of Al_2O_3 particles to decrease the grain sizes seemed to be derived initially from the fabrication and compaction of composite powders. The hard particle accelerated the fracture process of the aluminum particles [31]. The higher volume fraction of alumina phase resulted in smaller particle size of composite powders. And then when sintered, the finer grains of the composites could be obtained [16].

The microstructure of Al-MMCs was also influenced by Al_2O_3 particle size [32, 33]. Rahimian et al [24] studied the Al_2O_3 particle-reinforced aluminum composites with 3 μm, 12 μm and 48 μm particles. The results showed that the larger particle size of reinforcement led to larger grain size in the microstructure. It was not obscure to understand this because the additions of Al_2O_3 particles acted as a barrier against the movement of the grain boundaries during the sintering processes. As the particle size of the strengthening phase increased, the distance apart from the reinforcements was also increased. So the large grains were expected [24]. In the samples Al6061 with 3 vol% Al_2O_3 (30 nm, 1 μm and 60 μm), the same tendency of the grain size of matrix also had been detected. After milling and hot pressing, the grain size of composites was measured as 41 nm, 53 nm and 59 nm, respectively.

However, with the decrease of particle size, the agglomeration tendency between them was strengthened because of the large specific surface characteristics. In the 10 wt% Al_2O_3 particle-reinforced composite, the great amount of clustering had been occurred [24]. The results were also confirmed by Kok′s research [13], in which the microstructures revealed that the dispersion of the coarser particles was more uniform while the finer particles led to agglomeration and segregation. This phenomenon of the particles could be much more aggravated when nano-scaled alumina particles were the added. Fortunately, some improved processes, such as ball milling, extruding process, could be adopted to diminish the agglomeration to achieve the uniform distribution of particles in the matrix [30, 31].

It was well known that the higher sintering temperatures promoted the formation of denser structure due to higher diffusion rates [34], and stronger bonding between the particles [24]. However, with the rise of sintering temperature, the grain became coarsening over time, which led to lower strength and hardness [24]. This will be discussed in the following paragraphs. The grain coarsening could be compensated by the pin effect of the finer alumina. In the sample reinforced by 7 vol% nano-alumina, the grain size remained between 50 nm and 150 nm approximately [16]. Even heated for up to 480 min at 640°C, the overall neck growth and particle coarsening were hindered, although several neck junctions could be observed in the microstructure.

Density and Hardness

The density of alumina is 3.97 g/cm^3, while the density of pure Al and Al alloys are between 2.7-2.8 g/cm^3. Apparently, the density of alumina is higher than that of aluminum and aluminum alloys. As alumina was introduced to the mixture, it increased the sintered density. However, the

sintered density was not proportional to the amount of alumina since alumina addition led to the formation of pores in the microstructure [29]. The relative density was a criterion of evaluating a composite′s porosity and compactness. In general, any causes, if they induced formation of the porosity in the microstructure, the relative density would undoubtedly reduce.

Many researchers had proved this. The relative density was decreased from 99.0% (0% Al_2O_3) to 95.1% (20% Al_2O_3) in a Al-MMCs with micro-sized particles [29, 32]. In the samples sintered for 120 min at 640°C, a slight decrease in the relative density from 93.5% to 90.0% was noticed as the volume fraction increases from 1.0% to 7.0%. Whereas, in the samples with same sintering conditions, the effect of vol% of nano-alumina powder contents on relative density was noticeable. The addition of nano-alumina powder caused a considerable reduction in the relative density from 96.8% to 89.0%. It was suggested that a higher volume fraction resulted in a smaller interparticle spacing, which caused a negative effect on the sintering for the presence of the rigid particles at surfaces, and accordingly brought the decreasing of relative density [16]. Rahimian et al [29, 35] concluded that it was caused by reduction in compressibility of the powder and the inhibiting effect of alumina in the rearrangement of the particles during sintering, due to a great difference in the melting points of the matrix and the reinforcement.

The smaller reinforcement particle size had a similar effect with the higher volume fraction, both of which caused a smaller interparticle spacing. The increasing of Al_2O_3 particle sizes also increased the relative density of Al-MMCs. Raising the particle size of Al_2O_3 from 3 μm to 12 μm led to the relative density increasing from 96.5% to 96.8% [24]. In the sample with 7 vol% nano-alumina powders, the maximum relative density of 89.5% could be obtained, which was far lower than that of sample with submicron Al_2O_3 particle, of which the maximum relative density of 94.1% could be achieved [16]. However, some controversial results were also observed. In the reference [24], an increase in size from 12 μm to 48 μm resulted in a little low of 0.8% in the relative density. In Al6061 matrix nonocomposites with Al_2O_3 particles reinforcement, the relative density had an outstanding increasing from 78% to 98%, as the particle size changed from 1 μm to 30 nm. It seemed that the relative density showed a tendency of serrated changes with the particle sizes. Rahimian et al [24] attributed those to two concurrent consolidation mechanisms acting between the enforcement phase and the metal one, in which smaller alumina particle size led to less porosity increasing the relative density. Moreover, large alumina particles reduced the contact area between the aluminum particles, leading to higher porosity and lower relative density.

The relative density was also greatly influenced by the sintering temperature and sintering time. In a Al-MMCs with Al_2O_3 particles sintered at 500°C, the relative density was 96.8% [24]. Raising the sintering temperature to 550°C led to an increase of the relative density of 98.3%. At 600°C, the relative density of as high as 99.1% was obtained. With the extension of sintering time, the densification of composite was strengthened, and the relative density also increased. The relative density of a submicron alumina reinforced composites (3 vol%) increases rapidly to 93.0% during first 120 min [16]. However, over-extension sintering time was proved not to be always effective on the rise of the relative density. After a critical point, the relative density would be increased slowly or even leveled off. This phenomenon was observed by many authors [16, 29, 35]. Moreover, the rise of sintering temperature or/and length of sintering time usually induced the grain coarsening [24], as well as the rise of the fabricating cost.

According to the rule of mixtures, the addition of Al_2O_3 also increases the hardness of the composites since the hardness of alumina is much higher than that of matrix. However, hardness change was more complicated with processes compared to the relative density. Except for porosity, both the particles and the matrix also influenced the hardness of Al-MMCs [32]. Higher porosity causes an obvious reduction in hardness [16]. Accordingly, higher relative density results in increasing in hardness. Just mentioned above, the coarser grains also led to lower hardness [24].

The increasing of Al_2O_3 contents increased the hard-phase, which would increase the hardness [36-39]. However, the further increasing of Al_2O_3 contents decreased relative density, which would accordingly decreased the hardness. So was the sintering process, in which similar rules were also observed. The effects of sintering temperature and time should not be considered separately [24].

The increased temperature and extended time induced the sintering of composites, and induced the growth of grains simultaneously.

Mechanical Properties

The strength of Al-MMCs material is influenced by the microstructure and alumina reinforcement. Alumina particle has a strengthening effect, which is dominant at low concentrations. At the same time, it has another effect, which increases the amount of porosity in the composite material. It becomes more obvious at high concentrations [13, 34, 40]. It was suggested that there would be a critical alumina content, above or below which the mechanical strength of composites was both lowered [29, 41]. Some results proved this. In a Al-MMCs with 12 μm alumina particles, the peaks of yield strength and compressive strength were seen as the amount of 10wt% alumina was introduced into the matrix, in which, the yield and compressive strength of composites sintered at 550°C were 190 MPa and 278 MPa respectively. However, it was found that the minimum fraction of reinforcement phase was needed for strengthening Al-Al_2O_3 MMC [30, 33, 39]. Mazen [25] confirmed that the Al-2.5wt%Al_2O_3 showed reduction in strength compared to the unenforced matrix for the ineffective strengthening.

The rise in sintering temperature and the extending sintering time could contribute to increase in yield and compressive strength. This might be due to the denser structure under longer time and higher bonding strength between Al_2O_3 and matrix under higher temperature [42]. Yet, The large grain size of composites, which was induced by high sintering temperature and long sintering time, would decrease the strength of material.

The wear rate was greatly influenced by the hardness of composites [35, 43]. In a Al-MMCs sample, a reduction of 32% wear rate of the composites was achieved as the hardness increased from 47 HBN to 62 HBN [29]. Al-Qutub et al [37] reported that the hardness increased linearly with increasing the Al_2O_3 concentration in 6061Al-MMCs. The addition of 10vol% alumina in the composite increased the wear resistance by 45% on average. And with increase of alumina content, the wear resistance also improved. The improvement of wear resistances by 113% and 145% over the aluminum alloy were obtained respectively in the composite with 20vol% and 30vol% alumina. Similar result also obtained by Soma Raju et al [44], Hosking et al [45] and Hosseini et al [32].

However, the reduction of the wear rate was not completely consistent with the lift of hardness [41, 46]. A reduction of the wear rate was not observed as expected with the increase in hardness from 62 HBN to 74 HBN, which was caused by the increase in alumina content from 10wt% to 20wt% [29]. Some researchers ascribed it to the rise of porosity of composites, which decreased surface hardness and counteracted the effects of hardness [41, 47-49]. Moreover, with increasing the amount of Al_2O_3 particles, the agglomeration and cluster of particles induced the particles detach from the matrix to increase the wear rate, which would neutralize the effect of hardness of composites. The homogeneous dispersion in the matrix and good bonding with the matrix might be the keys to increase the wear resistance.

The effects of Al_2O_3 particle sizes on the wear rate had various results, some of which were opposite. The increasing Al_2O_3 particle size caused wear rate to increase in the Al6061-3 vol.% Al_2O_3 nanocomposite [32, 50]. They proposed that the finer of Al_2O_3 had changed the governing wear mechanism from delamination to abrasion. However, Hosking et al [45] had demonstrated a decrease in wear rate of 2024Al/Al_2O_3 composites with increasing particle size. The same tendency of wear rate with Al_2O_3 particle size was also observed by Kök et al [51], Roy et al [41] and Capus [52]. They considered that under the sliding wear testing conditions, the main wear mechanism was micro cutting and micro ploughing for the composites containing small particles, whereas it was grinding for the composites containing large particles [53]. Because of the different wear mechanisms, the wear resistance of the composites containing larger particles was higher than that of those containing small ones. The completely reverse results obtained by various authors might stem from ignoring the induced collateral effects by Al_2O_3 particles sizes, only focusing on the particle size itself.

Summary and Prospects

The advances have been reviewed on microstructure and properties of Al_2O_3 particulates reinforced Al-MMCs produced by the PM techniques. It is worth studying to control the characters of Al matrix and to optimize its bonding with Al_2O_3 particles. Outstanding progress has been made and still is potential research work to control the microstructures and to increase the properties of composites at a low cost. Most research so far has focused on more Al_2O_3 particles than aluminum matrix. The composite with smaller Al particles has proved to be endowed with higher values of the relative density and higher elastic moduli than that of composite with large Al particles [54]. The use of ultra-fine Al powders matrix will bring up new appealing benefits when compared to coarse powders.

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