Investigation on the Consolidation Behaviour of Aluminium/nano-SiC Composite Powders Using Non-Linear Compaction Equation

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Abstract: The densification response of aluminium powder reinforced with nanometric SiC particles (50 nm) during uniaxial compaction was studied. To determine the effect of SiC nanoparticles on the compressibility of the matrix, monolithic Al powder was also examined. The effect of SiC nanoparticles on the densification mechanisms, i.e. particle rearrangement and plastic deformation, was analysed using modified Cooper–Eaton equation. The results showed that with increasing the reinforcement volume fraction (up to 20 vol.-%), the contribution of particle rearrangement increases whilst the plastic deformation is limited. At high compaction pressures, the reinforcement particles significantly influence the yield pressure of the composite powder, retarding the densification. The influence of the reinforcement particle size is discussed in this paper.

1. Introduction

Discontinuously reinforced aluminium matrix composites have been developed and used for various applications, owing to their unique properties such as excellent wear resistance, high specific strength and thermal conductivity [1, 2]. Currently new development and research are focusing on the developing metal matrix nanocomposites with outstanding mechanical properties such as high yield strength and enhanced ductility [3-8]. In powder metallurgy techniques, the matrix and reinforcement particles are mixed and consolidated by various methods, e.g. hot deformation to fabricate almost full density products. Meanwhile, Kang et al. [9] have reported that the mechanical properties such as yield strength and hardness can be degraded by the reinforcement clustering, particularly at high volume fractions. Nevertheless, the compressibility of composite powders is remarkably lower than that of unreinforced matrixes [10]. In the past decades, considerable effort has been devoted to the development of empirical and theoretical compaction equations to describe the density–pressure relationships. By using linear compaction equations, such as Heckel[11], Panelli-Filho[12] and Ge[13], one can only study the role of plastic deformation (PD) on the densification response of composite powders. In order to study the role of particle rearrangement (PR), the non-linear equation proposed by Cooper and Eaton [14] was utilized [15]:

$$V^* = a_R \exp(\frac{-k_R}{P}) + a_P \exp(\frac{-k_P}{P}) \qquad (1)$$

where V^* is the total fractional volume compaction, a_R and a_P are dimensional coefficients which indicate the fraction of theoretical compaction achieved at infinite pressure by each particle rearrangement (PR) and plastic deformation (PD) process, k_R and k_P are constants with units of pressure. The contribution of each mechanism on the densification can thus be evaluated by comparison between the magnitudes of the constants. Also, there are a number of valuable analytical and numerical models, for example Martin and Bouvard [16] and Kim et al. [17], which enable prediction of the compaction behaviour of composite powders.

So far, it is known that the densification of composite powders is similar to that of unreinforced metals, but they exhibit lower densification rate due to stress partitioning effect. The consolidation of Al matrix blended with hard nanoparticles have scarcely been studied and the densification mechanism is not well understood. Recently, the effect of nanoscaled reinforcement particles on the compaction behavior of Al-5vol. %Al_2O_3 has been reported by simchi and co-workers [18]. The aim of present work is to study the effect of nano scaled SiC particles in a wide range of volume fractions on the consolidation behaviour of Al powder.

2. Experimental

Gas atomized aluminum powder with an average particle size of 40 μm was used as the starting matrix material. Nanometric SiC particles with the mean diameter of 40 nm was supplied from Alfa Aesar (Ward Hill, MA, USA). Different batches of Al-SiC

composite blends with varying volume fractions of 5, 10 and 20% were prepared. A Turbula mixer was employed for 30 min to prepare the blends. The tap density of powders was determined according to the ISO Standard 3953. The prepared powder blends were compacted in a cylindrical die with diameter of 15 mm using Teflon spray as die wall lubricant. In each run, 3 g powder was poured inside the die, taped and uniaxially compacted by using an AMSLER tensile/compression test instrument. The compacting pressure was varied between 10 to 400 MPa. The punch crosshead speed was 0.12 mm s^{-1}. Monolithic Al powder was also examined as the reference sample.

After ejection of compacts from the die, the density was measured by volumetric method. This method was employed through measuring the weight and dimensions of the compacts by using an accurate balance (±0.1 mg) and a micrometer (±0.1 mm). When the compaction pressure was low (for example <50 MPa) and a powder compact could not be attained, the in-die density was measured according to the mass and volume of the powder inside the die. Note that at such a low compaction pressure, the spring back is fairly low, thereby the difference between the in-die density and the out-die density is negligible. To investigate the consolidation mechanisms of matrix powder, the fracture surface of compacts were studied along the load direction. To prepare the suitable fracture surface, the compacts were sunk in liquid nitrogen. After bringing out the samples, they were immediately fixed and impacted to fracture. In order to fracture the specimens, a notch was prepared on the surfaces of each sample. Cooling the sample in liquid nitrogen results in brittle samples due to restriction of plastic deformation. The fracture surfaces were studied by SEM.

3. Results and Discussion

The Relative density of composite powders containing nanometric SiC particles at different compaction pressures is shown in Fig. 1. It is seen that, generally the addition of SiC particles decreases the compressibility of the Al matrix, so that compacts with lower relative density were obtained. Nevertheless, the densification of the composite powders at low pressure region (<50 MPa) is slightly higher than that of plain Al powder. This effect is more profound as the fraction of SiC increases. This can be attributed to the movement of SiC clusters to fill the interparticle pores. However, at high compaction pressures, the ceramic clusters and networks decrease the plastic deformability of the Al matrix, and thus retard the densification.

As it is seen in Fig. 1, at concentration >10vol% SiC, the densification curves approach a plateau at

relatively moderate compacting pressures, indicating a high yield pressure of the nanocomposite powder.
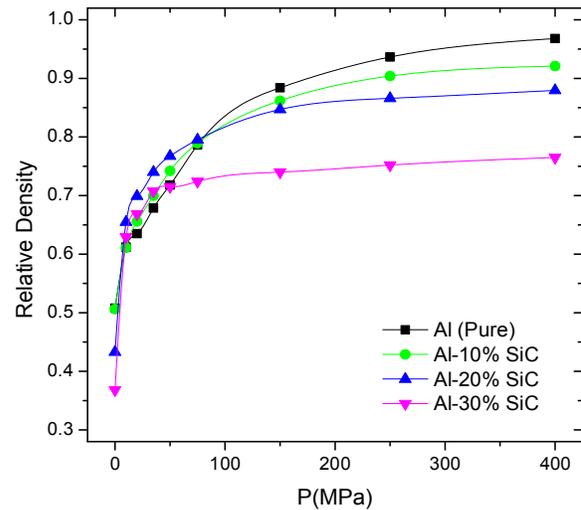

Figure 1. Relative density of nanocomposite powders at various SiC volume fractions.

3.1. Analysis of compaction behavior using Cooper-Eaton equation

In order to investigate the role of SiC particulates on densification behavior of Al matrix powder, modified Cooper-Eaton equation in which, V^* is replaced by the porosity (ε) changes during compacting process [15], was used. The experimental results were evaluated according to equation (1), by means of non-linear least square method to determine the constants of the equation. The results are presented in Table I. It is noticeable that the correlation coefficient (R) is very close to unity, which indicates accuracy of the analysis.

Table 1. The compaction coefficients of Al-SiC nanocomposite powders calculated by modified Cooper-Eaton equation

SiC Fraction%	a_R	a_P	k_R [MPa]	k_P [MPa]	R
0	0.31	0.78	3.7	83.62	0.999
5	0.36	0.58	5.2	70.2	0.999
10	0.48	0.35	2.5	53.9	0.999
20	0.58	0.07	3.8	154.1	0.999

The results indicate a remarkable effect of nanometric particles on rearrangement and plastic deformation coefficients. Also it is worthy to point

out that the consistently higher values for k_P compared with k_R, are an indication that filling of voids in second stage of consolidation (plastic deformation), needs considerably higher pressures. According to experimental results presented in Table 1, it is apparent that the addition of nanosized inclusions, imposes a higher influence on the consolidation behavior of composite powders. To highlight this observation, the compaction behavior of Al-SiC composite powders containing nanometric SiC particles was analyzed.

The result of calculations is demonstrated in Fig. 2 that shows the contribution of PR and PD on the deformation capacity of Al matrix. It appears that with increasing the volume fraction of reinforcement, the contribution of PR on the densification was increased, whilst the contribution of PD was decreased. This effect is very pronounced, particularly when high amount of the reinforcement particles were introduced. The results indicate that when the fraction of nanometric particles is relatively high ($\geq 10\%$), the contribution of PD decreases significantly.

In this circumstance, plastic deformation has a very small contribution in compaction process and densification is mainly induced by PR rather than PD. For instance, the contribution of plastic deformation in total densification of composite compacts at volume fraction of 10 and 20% is about 42 and 10%, respectively.

Fig. 3 shows the relationship between the coefficients of Cooper-Eaton equation and the volume fraction of reinforcements. One can notice the great influence of the nanometric reinforcement particles on the tap density of the composite powder. This effect is marginal at the low volume fraction of 5%, but at higher percentages, a remarkable decrease in tap density is observed. Thus, the lower tap density provides greater space for particle sliding at the early stage of compaction [10]. Consequently, higher a_R values are calculated at higher volume fractions of SiC nanoparticles.

It is noteworthy that the clusters and agglomerates of nanoparticles can be disintegrated under the applied pressure to fill the interparticle voids. On the other hand, at high compacting pressures a_P decreases with increasing the SiC content, indicating a reduced contribution of plastic deformation on densification of the nanocomposite powder. In fact, it becomes difficult for the Al matrix to deform and fill the gaps between the ultra-fine particles; so, lower density is achieved.
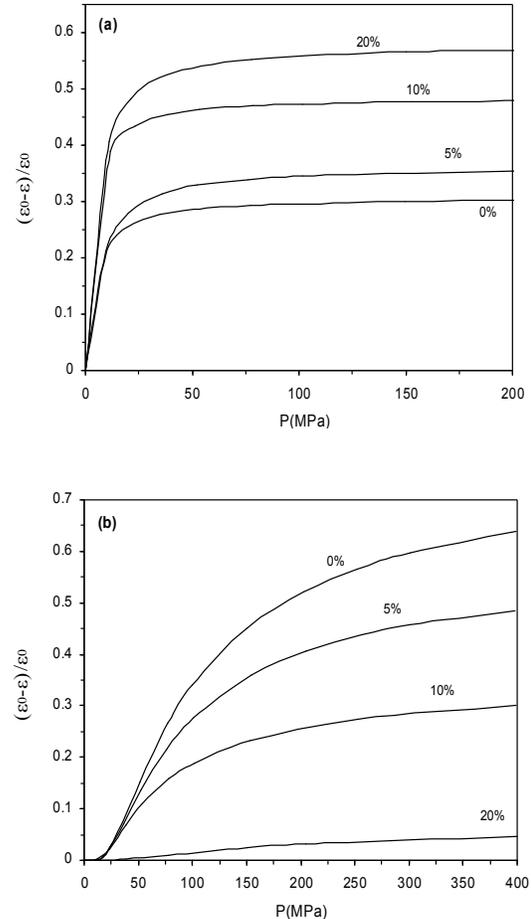

Figure 2. Effect of nano-sized SiC volume fraction on the contribution of particle rearrangement (a) and plastic deformation (b)
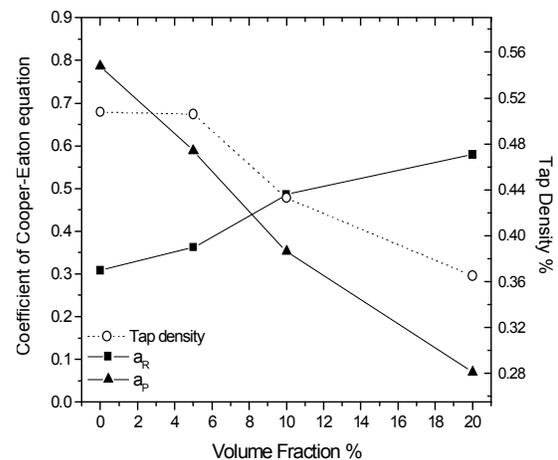

Figure 3. Effect of SiC nanoparticles on the tap density of Al powder and the coefficients of Cooper-Eaton equation.

Fig.4 indicates a profound effect of nanometric hard particles (Size ratio of 0.0025) on the tap density of composite powders. The ratio of the average size of SiC particles to the mean diameter of the Al particles are designated as the 'size ratio'. While this effect is marginal at low volume fraction of 5%, a significant decrease in the fractional density was observed at higher percentages. It is noticeable that with increasing reinforcement volume fraction, the detrimental influence of the nanoparticles increases.
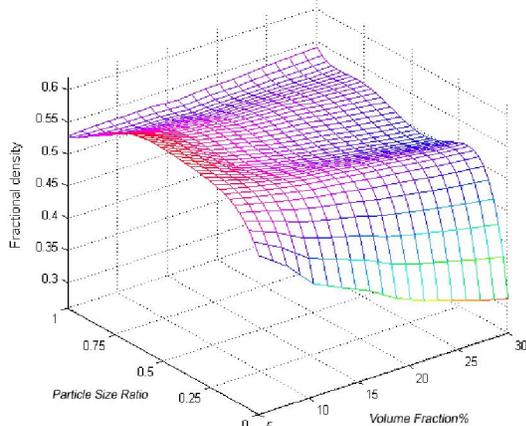

Figure 4. Effect of reinforcement size and volume fraction on the tap density of composite powders.

The bilateral effect of the reinforcement size and volume fraction on densification of the composite powders is shown in Figure 5. As it is seen, the highest density is achieved at higher size ratios when the fraction of SiC is relatively low (<10 vol%). It means that above the percolation threshold (10 vol%), the size ratio should be increased; otherwise, the densification is significantly retarded.
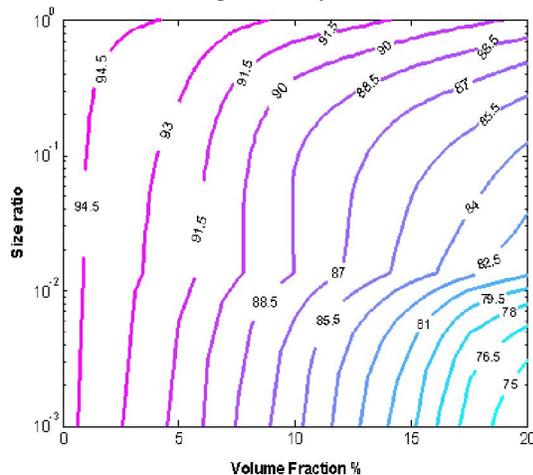

Figure 5. Effect of size ratio and volume fraction of the reinforcement on the density of composite powder at 300 MPa compacting pressure.

Fig 6. shows the representative SEM micrographs taken from the fracture surfaces of the Al powder compacted at 300 MPa. No evidence of ductile rupture, which is an indicator of the formation of large metal–metal contacts during pressing, is seen. The presence of the finer particles between the larger ones reveals that the applied load forced the spherical particles to move and fill the voids between the larger particles.
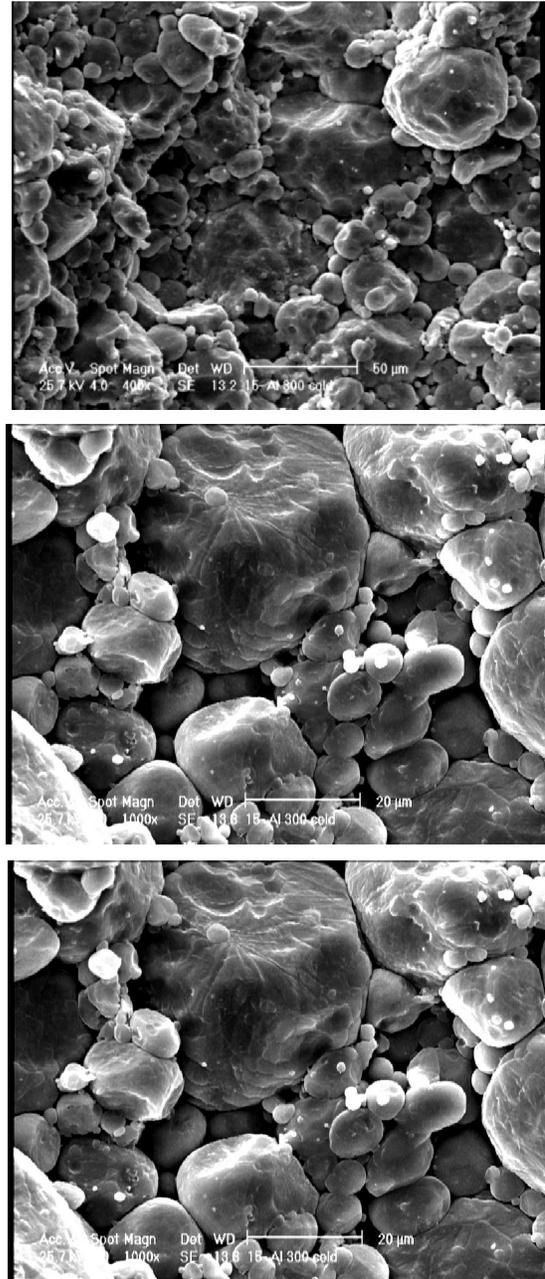

Figure 6. Fracture surface of Al powder compacted at 300 Mpa.

4. Conclusion

The consolidation behaviour of Al–SiC nanocomposite powders with varying reinforcement volume fraction during cold uniaxial compaction was studied. The results of Cooper-Eaton equation showed that with increasing the SiC content, the contribution of PR compared to PD increases. Meantime, the higher values for k_P compared with k_R, indicates that the filling of large holes (rearrangement stage) in the first stage of compaction, needs considerably lower pressures. This behavior is more pronounced in the case of composite compacts containing nanoscale SiC particles. This is owing to the low packing density, disintegration of clusters and the presence of particle size distribution in these composites. It was shown that at nano-scaled SiC concentration of $< \sim 8$ vol%, the plastic deformation of aluminium particles is the important mechanism of the densification. At higher concentration of nano-sized SiC, the particle rearrangement was found to be the dominant mechanism of consolidation.

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