Compaction Behavior of Aluminum Matrix Composites Reinforced with nano/micro Scale SiC Particulates

H.R. Hafizpour, M. Khoeini

Department of Materials Science, Saveh Branch, Islamic AZAD University, P.O. Box 39187-366, Saveh – Iran.
hamid_hafiz@alum.sharif.edu

Abstract: The compressibility behavior of particulate reinforced aluminum matrix composite powders was examined under uniaxial cold compaction. The effect of SiC volume fraction (up to 20%) with varying particle size (ranging from 50 nm to 40 μm) on the plastic deformation capacity of aluminum matrix was analyzed by using linear compaction equations. It was found that with increasing the volume fraction or decreasing the particle size of reinforcement, the densification coefficient decreases that means the less ability of material to deformation. Particularly, nano scaled inclusions impose higher influence on yield pressure of composite compacts. It was also shown that the effect of reinforcement size ratio on densification coefficient is more profound up to 10 vol.%. This article addresses the mechanisms involve in the densification of aluminum matrix nano-micro composites by using linear and non linear compaction equations.

[H.R. Hafizpour, M. Khoeini. Compaction Behavior of Aluminum Matrix Composites Reinforced with nano/micro Scale SiC Particulates. Journal of American Science 2011;7(7):753-759]. (ISSN: 1545-1003). http://www.americanscience.org.

Keywords: Composite powder; Densification coefficient; Al-SiC; Linear Compaction equation

1. Introduction

Metal Matrix Composites (MMC) are important engineered materials and discontinuously reinforced aluminium (DRA) alloy matrix composites are the most extensively researched and developed amongst them [1-3]. Particularly SiC reinforced Al alloy matrix has been attracting attention mainly due to their good attributes such as high specific strength and stiffness, excellent wear resistance, low coefficient of thermal expansion and high thermal conductivity [4,5]. Currently, new development and research are focusing on the developing metal matrix nanocomposites (MMNCs) with outstanding mechanical properties such as high yield and tensile strength, good creep resistance and enhanced ductility [6-8].

The powder metallurgy (PM) method is commonly employed means by which the metal matrix composites fabricated [9]. This route offers some major advantages including the ability to have complex shapes, reduction of production time and cost, the possibility of using high volume fraction of the reinforcement, homogeneous distribution of the reinforcement in the matrix without undesirable diffusive process and good dimensional tolerance [10-12]. In PM techniques, the matrix and reinforcement particulates are blended and consolidated by various methods, e.g. hot deformation to fabricate almost full density products. Nevertheless, the compressibility of composite powders is remarkably lower than that of unreinforced matrixes. This effect is more noticeable with increasing reinforcement content, which often produces insufficient strength to support secondary processing like sintering, machining or extrusion [13]. Also, Ceramic powders show a tendency for agglomeration due to van der waals attraction [14], specially In the case of composite powders composed of ultra-fine particulates. Thus, it is important for optimizing properties, because clustering induces non uniform stress distribution in the materials, leading to degraded mechanical properties [15]. Hence, it would be very useful to determine the effects of particle size and volume fraction on the consolidation behavior of nano-micro scaled composites.

It is apparent that compaction is an important step which strongly influences the final properties of compacts. A glance through open literature reveals that considerable effort has been devoted to the development of empirical and theoretical compaction equations to describe the density-pressure relationships for the compaction of powders. Since the first compaction equation published by Walker [16], more than 20 different compaction equations have been proposed [17]. For instance, the modified Heckel [18], Panelli-Filho [19] and Ge [17] equations are the most commonly ones, that used today. These equations are expressed as follows:

$$Ln(\frac{1}{1-D}) = K_1 P + B_1 \quad \text{Heckel (1)}$$

$$Log[Ln(\frac{1}{1-D})] = K_2 Log(P) + B_2 \quad \text{Ge (2)}$$

$$Ln(\frac{1}{1-D}) = K_3 \sqrt{P} + B_3 \quad \text{Panelli-Filho (3)}$$

Where:

K_1, K_2, K_3: Powders ability to densify by plastic deformation (Slope of the curves). K parameter is inversely related to the ability of the material to deform plastically.

B_1, B_2, B_3: Coefficients that represent the density of powders in the beginning of the compaction, D: Relative density of the compacted material and P: applied pressure.

It is worth to mention that owing to the complexity in densification of mixed powders, investigation on compaction behavior has been mainly focused on monolithic powders, but it has been extended to composite powders recently [23]. Lange et al. [24] studied the densification behavior of mixed aluminum and steel powders under cold compaction. Gurson and McCabe [25] examined the yield function for mixed metal powders by using data from triaxial compression test. Kim et al. [26] proposed a densification model for mixed copper and tungsten powders under cold isostatic pressing and die compaction. The analysis of consolidation behavior of Al-SiC composite powders under monotonic and cyclic load by using Heckel equation has recently reported by simchi et al. [5]. Kim et al. [27] employed a hyperbolic cap model with the constraint factors proposed by Storåkers et al. [28] to investigate the densification behavior of Al alloy powder mixed with zirconia inclusions.

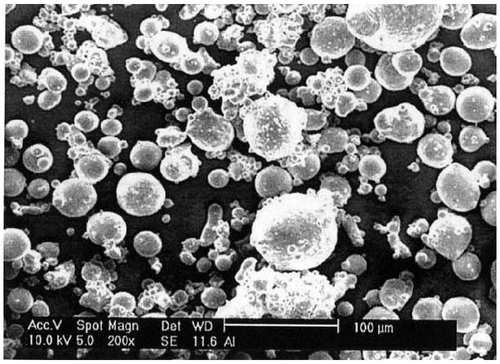
So far, it is known that the densification of composite powders is similar to that of unreinforced metals, but they exhibit lower densification rate due to stress partitioning effect.

The objective of present research is to elucidate the effects of nano-micro sized reinforcement at different volume fractions on the consolidation behavior of Al-SiC composites. Based on experimental results and in accompanying with linear compaction equations, the densification mechanisms of Al-SiC composites were investigated.

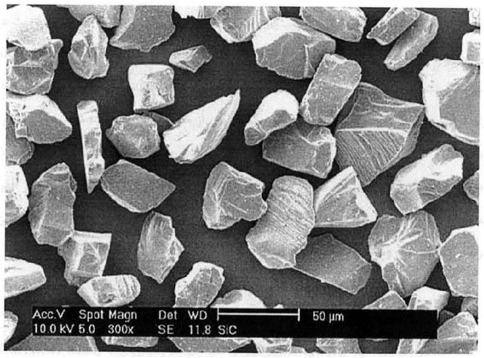
2. Experimental procedure

Nitrogen gas atomized Al powder with mean particle diameter of 40 µm was used as the matrix material. Commercial available SiC powders with the average particle size of 0.05, 1, and 40 µm were used as the reinforcement. Fig. 1 shows the morphology of Al and SiC particles taken by electron microscopy. The Al and nanoscaled SiC particles have nearly spherical shape whilst the microscaled SiC is angular type.

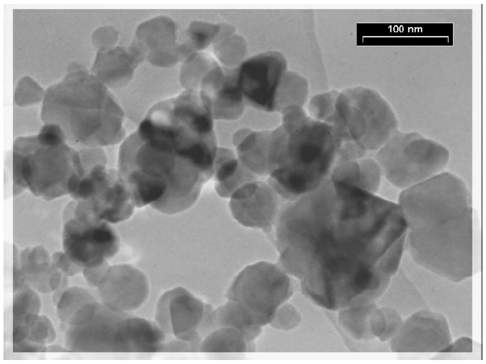
Different batches of Al-SiC composite blends with varying volume fractions of 5, 10 and 20% were prepared. A Turbula T2C mixer (Basel, Switzerland) was employed for 30 min to prepare the blends. To prevent the problem of static charge induced agglomeration, wet mixing using a polar solvent (n-butanol) was afforded [9]. The composite mixtures were then dried at 100 °C in a small electric vacuum oven. The tap density of powders was determined according to the ISO Standard 3953; 1993.



a) Al (40 µm)



b) SiC (40 µm)



c) SiC (50 nm)

Figure 1. Morphology of starting materials taken by SEM (a, b) and TEM (c).

The prepared powder blends were then compacted in a cylindrical die with diameter of 15 mm. Die wall lubrication was afforded using polytetrafluoroethylene (PTFE) spray. 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. The 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). Note that the specimens were green and unsintered, so that water displacement method is hard to be employed for green parts. Different runs were repeated for at least three times to verify the reproducibility of the attained data. Meanwhile, 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.

3. Results and Discussion

3.1. Compressibility curves

In order to highlight the role of nanoscaled particulate reinforcement on the compressibility response of Al matrix composite, the void fraction of compacts at different compaction pressures is calculated and results are shown in Fig. 2 the corresponding curve of unreinforced Al powder is included in the graph for comparison. As can be seen, the curves indicate the typical powder void fraction behavior for metallic powders, i.e. the void fraction decreases with increasing the compaction pressure with a decelerating rate. This means that different mechanisms can occur during compaction process. As received Aluminium powder is ductile so possesses good compressibility, But When the hard ceramic nanosized particles were added, two important changes in the curves can be highlighted. First, a high densification rate of the composite powders at low pressure region (<50MPa) compared to the gas atomized Al matrix powder. This effect is more profound as the volume fraction of inclusion increases. Second, the densification rate of composite compacts at high pressures is lower than that of the gas atomized elemental powder. This behavior can be attributed to the detrimental effect of the formation of ceramic clusters and networks on the plastic deformation ability of metal matrix. Also it can be observed that by increasing the volume fraction of reinforcement from 10 to 20%, the densification curves, reach almost to a plateau at relatively moderate compacting pressures.

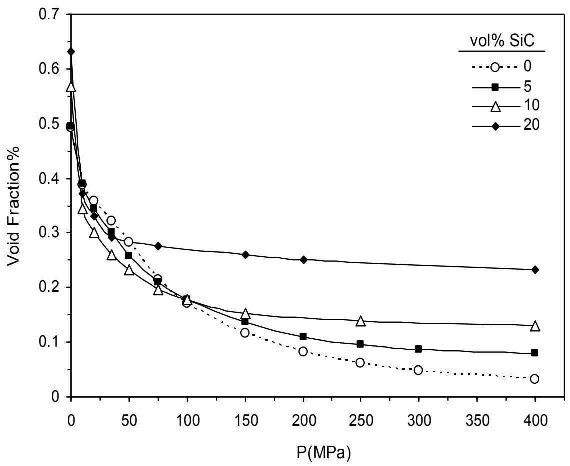


Figure 2. Void fraction of Al-SiC composite powders (the size ratio of 0.00125) as a function of compaction pressure at various SiC volume fractions.

Fig. 3 shows the effect of reinforcement particle size on the consolidation behavior of Al-SiC composites at volume fraction of 10 and 20 percent. In order to highlight the role of particle size, the ratio of the average size of reinforcement particles to the mean diameter of the matrix particles are designated as the 'size ratio'. The following statements can be enumerated:

1. With decreasing the reinforcement particle size from 40 µm to 50 nm, the densification rate increases at low pressure region. It is seen that the composite powder contained finer particulates, is densified with a higher rate.
2. At high compaction pressures (>200MPa) and by decreasing the inclusion particle size, the densification rate decreases sharply, especially in the case of composite compacts containing nanoscale SiC particles.
3. With decreasing the inclusion particle size from 40 to 1 µm, the deleterious effect of size ratio on densification response of Al matrix is remarkable (Fig. 3a), but at higher volume fractions (20 vol.-%), the density level of compacts is decreased almost with a constant rate (Fig. 3b). It is known that the consolidation mechanism of metal powders in a rigid die is usually considered in four stages including sliding and particle rearrangement, plastic deformation of ductile powders, fragmentation of brittle solids, and elastic deformation of bulk compacted powders [18]. Although these stags may occur concurrently according to the powder characteristics and pressure level, at the early stage of the densification process at low pressures, particles sliding, deformationless restacking or rearrangement, and breaking down the bridges (formed during die filling) and agglomerates of the primary particles are

the dominant mechanisms [18,29].

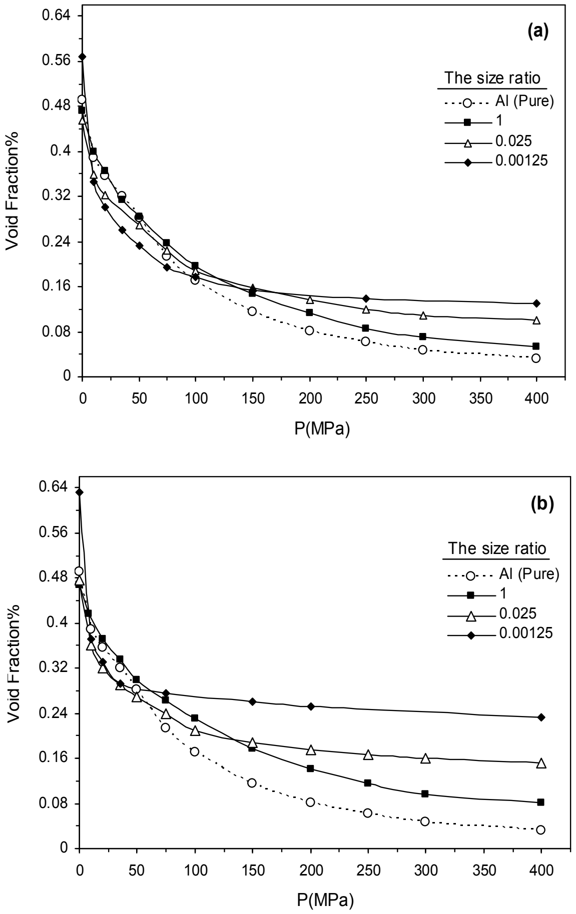


Figure 3. Effect of size ratio on densification of (a) Al-10% SiC and (b) Al-20%SiC composite powders.

When applied pressure increases, the movement of the particles is restricted and the energy applied to the powder compact is spent generally through the process of deformation and friction losses [29]. This regime is often referred to as stage II. Particle interlocking generates plastic deformation, which is first localized at the contact areas between particles [30]. Therefore, at higher pressures, plastic deformation of ductile powders becomes the predominant densification mechanism. Experimental results in this work indicated that the densification behavior of examined mixed powders show the same features as metal powders (Fig. 3). As it is seen, gas atomized aluminium powder possesses good compressibility so that uniaxial compaction at 400 MPa led to a green density as high as 97% theoretical. When ceramic particles were added, the density-pressure curve is somewhat similar to the unreinforced Al, but the densification rate is lower. Note that both SiC volume fraction and size influenced the densification of the Al matrix, although to varying degree dependent on the applied pressure level. Effect of these parameters on the plastic deformation response of Al can be evaluated as below.

3.2. Analysis of compaction behavior using linear compaction equations

The estimate of the powder plastic deformation capacity during the densification process by compaction equations is useful to evaluate the results [5]. In order to clarify the role of reinforcement particle size and volume fraction on the compressibility behavior of Al-SiC composites, the Panelli-Filho and Ge equations were selected among the most widely used ones, because the good agreement was obtained when the experimental data were fitted by these equations. In Fig. 4, the effect of volume fraction of nanosized reinforcement on the compaction response of Al matrix by using Ge equation is illustrated. (The results were calculated by the best fit – linear method). According to the results of Fig. 4, the monolithic Al powder has the highest K value, indicating the higher plastic deformation capacity. Also it can be seen that the addition of extremely small nanometric particulates, decreased the K value significantly, that means the less ability of material to deformation.

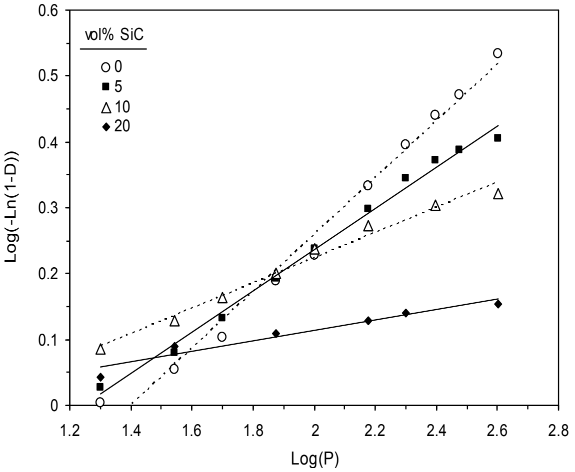


Figure 4. Effect of the volume fraction of nanometric SiC particulates on the plastic deformation capacity of Aluminum matrix by using Ge equation.

In Fig. 5 we attempt to clarify the role of inclusion particle size on the plastic deformation ability of Al-10%SiC composites by using Panelli-Filho equation. It is seen that the plastic deformation capacity of composite compacts is depended on the size ratio of the reinforcement to matrix particles. It is evident that, by decreasing the size ratio from 1 to 0.00125, the densification coefficient, considerably decreased.

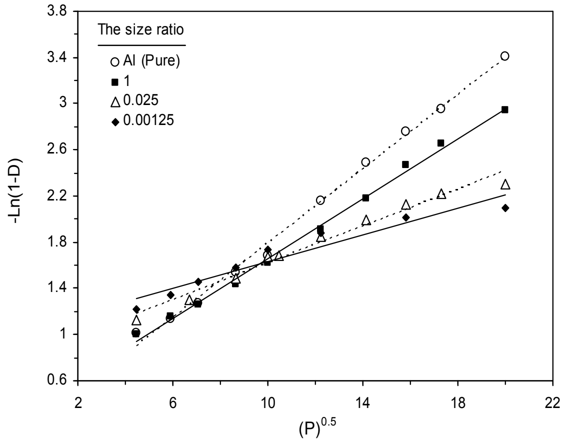


Figure 5. Effect of reinforcement size ratio on the plastic deformation capacity of Al-10 vol.%SiC composite powders by using Panelli-Filho equation.

The experimental data was evaluated according to Eq. 2 and Eq. 3 by linear regression analysis to determine the plastic deformation capacity of materials. The results of calculations are shown in Table I.

It is visible that, in most cases these equations give correlation coefficients close to unity for the compaction of composite powders. According to the calculated results presented in Table I, one can notice that the reinforcement size ratio and volume fraction, remarkably influence the plastic deformation response of composite powders. This effect is more significant in the case of composite powders containing nanometric particulates, especially at high volume fractions.

The bilateral effects of reinforcement volume fraction and size ratio on deformation ability of composite compacts can be evaluated by Fig. 6. This figure illustrates the densification coefficient of each equation (K_1 for Panelli-Filho and K_2 for Ge) as a function of SiC volume fraction and particle size. As Fig. 6 shows, the detrimental influence of reinforcement size ratio is more remarkable up to 10 vol.-% reinforcement.

In other words, when finer reinforcement particles are used (size ratio of 0.025 and 0.00125), the densification coefficient decreased significantly. This effect is more noticeable up to 10 vol.-%, but with increasing the volume fraction of inclusions, the reducing rate of densification coefficient, is almost similar for various particle size ratios. It is apparent that by decreasing the reinforcement particle size, the ceramic particulates tend promote the formation of clusters. Thus it is difficult for the Aluminum matrix to deform and fill the voids between the reinforcement clusters. This effect is more pronounced when nanometric reinforcement was used. In this circumstance, matrix particles are surrounded by extremely small SiC particles. Consequently, it seems that up to 10 vol.-% reinforcement, the clustering of inclusions plays significant role, but at higher volume fractions, the presence of percolation network of hard inclusions that supports a part of applied pressure elastically, restricts the plastic deformation capacity of materials significantly [31]. This outcome is in consistent agreement with the results of modelling performed by Kim et al [27].

Table 1. Calculated results of linear regression analysis on the compaction of composite powders.

Sic Content	**Ge**		**Panelli Filho**	
	K (MPa^{-1})	R	K (MPa^{-1})	R
0 Vol.%	0.43	0.99	0.16	0.99
5%SiC,50nm	0.31	0.99	0.10	0.99
10%SiC,50nm	0.21	0.99	0.06	0.96
20%SiC,50nm	0.08	0.98	0.02	0.95
5%SiC,1µm	0.34	0.99	0.11	0.99
10%SiC,1µm	0.25	0.99	0.08	0.99
20%SiC,1µm	0.18	0.99	0.05	0.98
5%SiC,40µm	0.40	0.99	0.14	0.99
10%SiC,40µm	0.37	0.99	0.13	0.99
20%SiC,40µm	0.33	0.99	0.10	0.99

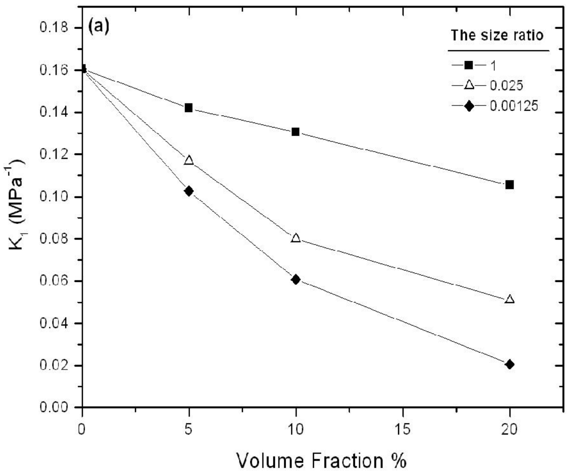
Note: R= Correlation Coefficient, K= Densification Coefficient

In order to get an insight about the deformation capacity of composite compacts, we call P_y (P_y=1/K) as yield pressure, since a material with higher K-value achieves higher density at a constant applied pressure.

Fig. 7 shows that, the addition of reinforcement particles increases the yield pressure required for the plastic deformation of composite powder, leading to a decrease in densification rate. For instance when 10 and 20 vol.-% nanometric SiC particles are used, the yield pressure is about 3 and 8 times more than that of unreinforced Aluminum, respectively. In spite of general good agreement between experimental data and calculations, some limitations arise in the application of linear equations. For instance it is seen that with decreasing the SiC particle size to nanosize and increasing the volume fraction, deviations from linear slope increases.

4. Conclusion

Densification behavior of aluminum matrix powder reinforced with nano-micro sized SiC particulates during cold compaction was investigated. Experimental results were obtained for mixed Al-SiC powders under uniaxial die compaction. It was shown that the compressibility behavior of nano-micro composite powders exhibit the same features as the typical metal powder compaction. The densification is obtained through two major mechanisms, Particle rearrangement and plastic deformation. It was found that with decreasing the reinforcement particle size, the densification rate in the first stage of compaction, increases but its decreases in second stage. This effect is very noticeable in the case of composite compacts containing nanometric SiC particles, particularly at higher volume fractions. Linear compaction equations were used to determine the densification mechanisms of composite compacts. Results revealed that the addition of reinforcement particles increases the yield pressure required for the plastic deformation of composite powders. Also it can be deemed that up to 10 vol.-% reinforcement, the detrimental effect of inclusion clustering on densification plays significant role, but at higher volume fractions, presence of the percolation network of hard inclusions that supports a part of applied pressure elastically, restricts the plastic deformation capacity of compacts.



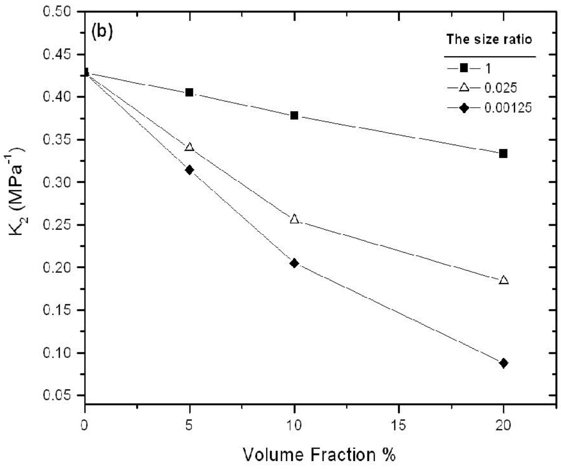


Figure 6. Densification coefficient of Al-SiC composite powder as a function of SiC particle size and volume fraction using Panelli-Filho (a) and Ge (b) equations.

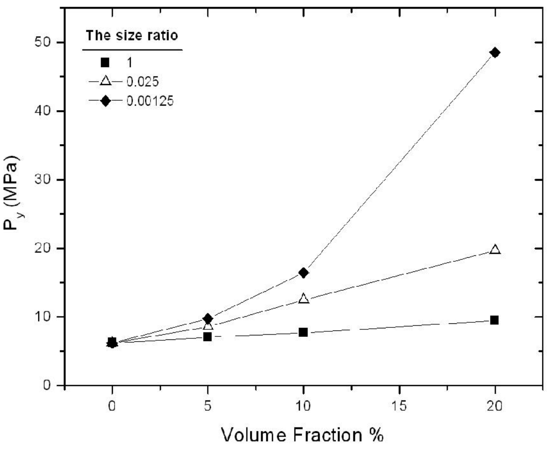


Figure 7. Yield pressure of Al-SiC composite powder as a function of reinforcement particle size and volume fraction by using Panelli-Filho equation.

References

1. K. S.Raju, V. V. Bhanu Prasad, G. B. Rudrakshi and S. N. Ojha, 2003, PM processing of Al-Al_2O_3 composites and their characterization, Powder Metallurgy, 46 (3) 219-223
2. Ü. Cöcen, K. Önel, 2002, Ductility and strength of extruded SiCp/aluminium-alloy composites, Composites Science and Technology, (62) 275-282
3. V.V. Bhanu Prasad, B.V.R. Bhat, Y.R. Mahajan and P. Ramakrishnan, 2002, Structure-Property Correlation in Discontinuously Reinforced Aluminium Matrix Composites as a Function of Relative Particle Size Ratio, Materials Science and Engineering, 337A 179-186

4. Z. Gnjidic, J. Grbovic, M. Mitkov and D. Bozic, 2003, Influence of SiC particles on compressive strength of sintered aluminium alloy, Powder Metallurgy, 46 (1) 21-24
5. A.H. Tavakoli, A. Simchi and S.M. Seyed Reihani, 2005, Study of the compaction behavior of composite powders under monotonic and cyclic compaction, Composites Science and Technology, (65) 2094-2104
6. M. O. Lai, L. Lu and W. Laing, 2004, Formation of magnesium nanocomposite via mechanical milling, Composite Structures, (66) 301-304
7. H. Ferkel and B. L. Mordike, 2001, Magnesium strengthened by SiC nanoparticles, Materials Science and Engineering, 298A 193-199
8. Y. C. Kang and S. L. Chan, 2004, Tensile properties of nanometric Al2O3 particulate-reinforced aluminium matrix composites, Materials Chemistry and physics, (85) 438-443
9. V.V. Bhanuprasad, R.B.V. Bhat, A.K. Kuruvilla, K.S. Prasad, A.B. Pandey and Y.R. Mahajan, 1991, P/M Processing of Al-SiC Composites, The International Journal of Powder Metallurgy, 27 (3) 227-235
10. B. Ogel and R. Gurbuz, 2001, Microstructural characterization and tensile properties of hot pressed Al-SiC composites prepared from pure Al and Cu powders, Materials Science and Engineering, 301A 213-220
11. X. J. Xin, P. Jayaraman, G. Jiang, R. H. Wagoner and G. S. Daehn, 2002, Explicit finite element method simulation of consolidation of monolithic and composite powders, Metallurgical and Materials Transactions A, 33A 2649-2658
12. G.Jiang, G. S. Daehn and R. H. Wagoner, 2003, Observations on densification of Al-Al_2O_3 composite powder compacts by pressure cycling, Powder Metallurgy, 46 (1) 78-82
13. G. Jiang, W. Wu, G. S. Daehn and R. H. Wagoner, 2000, Experimental and Numerical Investigation of Idealized Consolidation Part II:Cyclic Compaction, Acta Materialia, 48 (17) 4331-4335
14. K. T. Kim, S. W. Choi and H. Park, 2000, Densification behavior of ceramic powder under cold compaction, Transactions of the ASME, (122) 238-244
15. Z. Zhou, H. X. Peng, Z. Fan, and D. X. Li, 2000, MMCs with controlled non-uniform distribution of submicrometre Al2O3 particles in 6061 aluminium alloy matrix, Materials Science and Technology, (16) 908-912
16. A. Hassanpour and M. Ghadiri, 2004, Distinct element analysis and experimental evaluation of the Heckel analysis of bulk powder compression, Powder Technology, (141) 251-261
17. Ge Rong-de, 1991, A New Powder Compaction Equation, The International Journal of Powder Metallurgy, 27 (3) 211-216
18. P. J. Denny, 2002, Compaction Equations: A Comparison of the Heckel and Kawakita Equations, Powder Technology, (127) 162-172
19. R. Panelli and F. A. Filho, 2001, A study of a new phenomenological compacting equation, Powder Technology, 114 255-261
20. Y. Ozaki, S. Unami and S. Uenosono, 2002, Pre-mixed Partially Alloyed Iron Powder for Warm Compaction: KIP Clean Mix HW Series, Kawasaki Steel Technical Report, No. 47, December 48-54
21. K. Kondoh, R. Watanabe and H. Hashimoto, 2000, Analysis of Compaction Behavior of Wet Granulated Aluminium Alloy Powder, Powder Metallurgy, 43 (4) 359-363
22. A. R. Cooper and L. E. Eaton, 1962, Compaction Behavior of Several Ceramic Powders, Journal of the American Ceramic Society, 45 (3) 97-101
23. K.T. Kim and J.H. Cho, 2001, A Densification Model for Mixed Metal Powder under Cold Compaction, International Journal of Mechanical Science, (43) 2929-2946
24. F. F. Lange, L. Atteraas, F. Zok and J. R. Porter, 1991, Deformation Consolidation of Metal Powders Containing Steel Inclusions, Acta Metallurgica et Materialia, 39 (2) 209-219
25. A.L. Gurson, T.J. McCabe, 1992, Experimental determination of yield functions for compaction of blended metal powders, Advances in Powder Metallurgy and Particular Materials, (2) 133-145, MPIF, Princeton, NJ.
26. K. T. Kim, J. H. Cho and J. S. Kim, 2000 Cold Compaction of Composite Powders, Journal of Engineering Materials and Technology, 122 (1) 119-128
27. K. T. Kim, S.C. Lee and H. S. Ryu, 2003, Densification Behavior of Aluminium Alloy Powder Mixed with Zirconia Powder Inclusion under Cold Compaction, Materials Science and Engineering, 340A 41-48
28. B. Storåkers, N. A. Fleck and R. M. McMeeking, 1999, The Viscoplastic Compaction of Composite Powders, J. Mech. Phys. Solids, (47) 785-815
29. A. R. Poster, 1962, Factors Affecting the Compaction of Tungsten Powders, Powder Metallurgy, (9) 301-315
30. D. Poquillon, J. Lemaitre, V. Baco-Carles, Ph. Tailhades, and J. Lacaze, 2002, Cold compaction of iron powders-relations between powder morphology and mechanical properties, Part I: Powder preparation and compaction, Powder Technology, (126) 65-74
31. G. Jiang, G. S. Daehn and R. H. Wagoner, 2001, Inclusion Particle Size Effects on the Cyclic Compaction of Powder Composites, Scripta Materialia, (44) 1117-1123

7/3/2011