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Clustering model on the tensile strength of PM processed SiCp/Al composites

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ABSTRACT

Reinforcement clusters in the powder metallurgy (PM) processed SiCp/Al composites were divided into two types: the non-contacted clusters and the contacted clusters. Based on this conception and the critical volume fraction of reinforcement, a cluster strength model was proposed to calculate the strength of the PM SiCp/Al composites with clustering. The calculated strengths of the as-pressed and the as-extruded SiCp/Al composites were in good agreement with the experimental results. The model could also quantitatively explain the phenomena that the strength of the PM composites began to decrease above some volume fraction of reinforcement.

1. Introduction

Metal–matrix composites (MMCs) reinforced with ceramic particles are of interest for a variety of industrial applications due to higher specific modulus, strength and wear resistance in comparison with unreinforced alloys [1–3]. Powder metallurgy (PM) processed composites with good mechanical properties can be produced when the reinforcements are homogeneously distributed in the matrix [1,2]. However, clustering is difficult to avoid in the case of a large reinforcement concentration or a large particle size ratio of matrix powders to reinforcement powders. Many investigations [3–7] demonstrated that the clustering could degrade the tensile properties of the composites. However, mechanism responsible for the degradation of tensile properties is still not well understood.

Some attempts investigated the clusters on the basis of a critical volume fraction ($V_{critical}$) for the PM processed composites [8,9]. It was reported that the clusters would be generated provided that the volume fraction of reinforcements was larger than the $V_{critical}$, while no cluster appeared in the opposite situation. In our previous article [10], we also built a critical volume fraction model of reinforcement to evaluate the distribution of the reinforcement in the composites. However, the effects of clustering on the mechanical properties were not quantitatively evaluated in that article. Investigations on the mechanical properties of the composites [11–14] indicated that the rule of mixing model and the shear lag model were effective to predict strength. Nevertheless, the above models were based on the homogeneous distribution of the reinforcement. The situations that the composite had the reinforcement clustering were seldom discussed.

In this article, the critical volume fraction of the reinforcement was used to determine the concentration of the clustered reinforcements. And a cluster strength model based on the modified shear lag was proposed to calculate the yield strength (YS) and ultimate strength (UTS) of the composites. The effects of clustering on the tensile strength of the as-pressed SiCp/Al composites were discussed. Furthermore, the model was examined using the strength data of the as-extruded composites from other investigators.

2. Experimental procedure

SiC particulate (SiCp) reinforced 2009Al-based MMCs were used in this article. The composites with the reinforcement volume fractions of 15, 20, 25, 30 and 35 vol.% were fabricated using a PM route with a Al–4.5Cu–1.4 Mg alloy (nominal composition) as the matrix and α-SiC as the reinforcement. The mean size of aluminum powders was 13 μm. For minimizing the influence of the reinforcement rupture [15], finer SiCp with an average size of 3.5 μm were used.

The as-received SiC powders were dried at 423 K for 5 h, and then mechanically mixed with the Al powders in a bi-axis rotary mixer with a rotation speed of 50 rpm and a large ball to powder ratio of 10:1. No process control agent was added. According to Ref. [10], this mixing process with a large ball to powder ratio could introduce deformation and cold-welding of the aluminum powders so as to increase the $V_{critical}$ and improve the SiC distribution. However, different from high energy mill process, this mixing process did not introduce much fracture of the cold-welding powders. Thus the width of the layer in lamellar powders was

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easily determined, which could then be used to calculate the $V_{critical}$ according to our previous investigation [10].

The as-mixed powders were cold pressed in a cylindrical die, degassed at 673 K for 1 h and then hot-pressed at 853 K under a pressure of 80 MPa, producing the composite billets 60 mm in diameter and 80 mm in height. The as-pressed composites were solutionized at 768 K for 1 h, water quenched, and then naturally aged for 96 h (T4).

Microstructures of the as-pressed composites were observed using optical microscopy (OM, Axiovert 200 MAT) and scanning electron microscopy (SEM, Quanta 600). Tensile specimens with a gauge diameter of 5 mm and a gauge length of 25 mm were machined from the T4-treated samples along the axis direction, in accordance with the Chinese National Standard GB/T228-2002. Tensile testes were performed at room temperature and an initial strain rate of $1 \times 10^{-3}\ s^{-1}$ on an AG-100kNG tensile tester. YS and UTS were determined from two specimens to ascertain reproducibility. The density of the composite was determined using the Archimedean principle. Distilled water was used as the liquid for the measurements. The results were averaged over three independent measurements.

3. Results

The SiC distributions in various composites are shown in Fig. 1. For the composite with a volume fraction of 15 vol.%, the SiCp were homogeneously distributed with a pronounced streamline-like structure, resulting from the deformation and cold-welding process dominant during the mixing process (Fig. 1a). For the composites with higher reinforcement contents ($\geqslant$20 vol.%), although the distributions of the SiCp were still relatively homogeneous, clusters began to appear (Fig. 1b–d). A large amount of reinforcement particles came into contact with each other for the SiC concentration of 35 vol.%, as shown in Fig. 1d. Some pores induced by cluster could be seen in the particle clusters. The results were similar to the previous studies [8–10]. According to the explanation for the cluster formation, when the SiCp concentration was higher than the $V_{critical}$, the cluster would form.

Fig. 2 shows the theoretical and measured density of the composites with different reinforcement concentrations. The measured density deviated from the theoretical one when the reinforcement concentration was larger than 20 vol.% due to the porosity formation in the clusters. And the deviation was especially obvious at the SiC concentration of 35 vol.% due to increased porosity formation, which was in accordance with OM observations (Fig. 1d).

Fig. 3 shows the variation of the strengths of the composites with the reinforcement concentrations. Adding the reinforcement to the matrix alloy led to the increased YS and UTS. However, the YS began to decrease at the SiC content of about 30 vol.% and the UTS began to decrease at the SiC volume fraction of about 20%, due to the effect of the reinforcement clusters.

Fig. 4 shows typical fractographs of two hot-pressed composites with different SiC contents. The fractographs exhibited a characteristic of small smooth faces instead of obvious deep dimples. This might be resulted from the existence of alumina film on the surface of the Al powders. The alumina layer undermined the bonding between the Al powders [16,17], thus it became easy for void nucleation and crack propagation along the boundaries between the Al powders. The fractograph of the composite with 30 vol.%

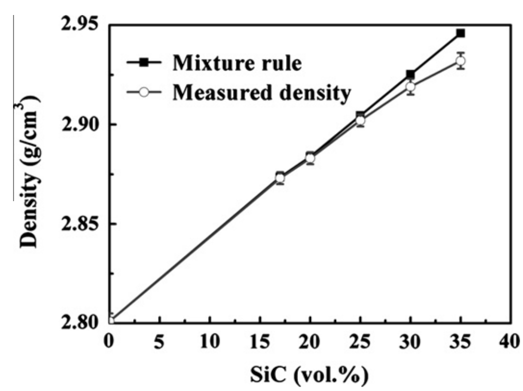

Fig. 2. Density at different reinforcement concentrations.

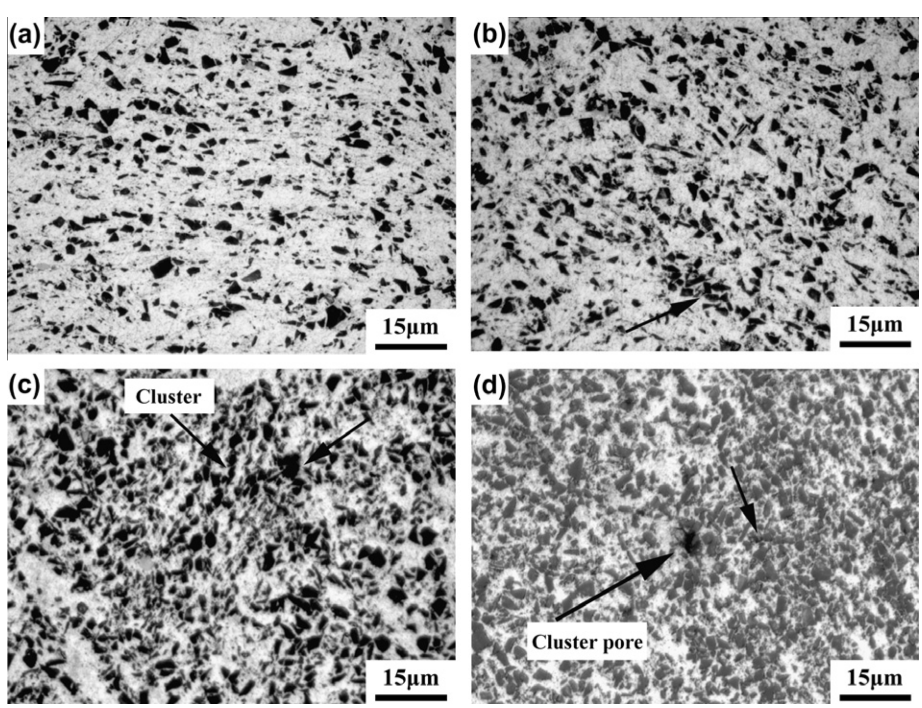

Fig. 1. Microstructure of SiCp distribution at different concentrations: (a) 15 vol.%, (b) 20 vol.%, (c) 30 vol.%, and (d) 35 vol.%.

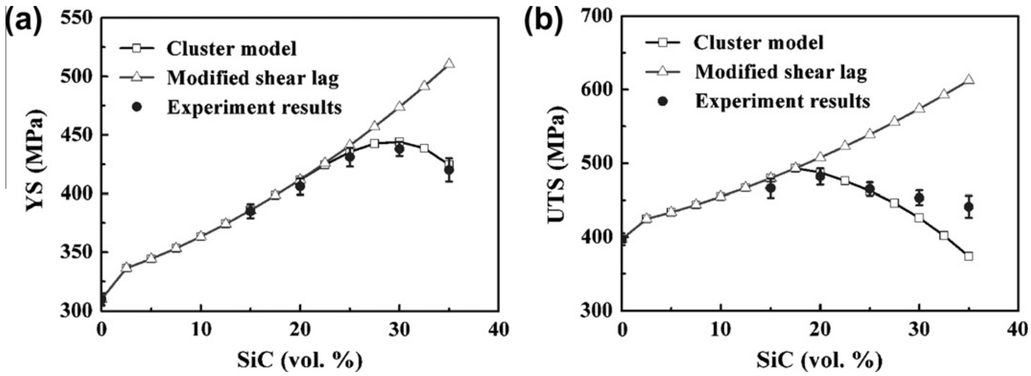

Fig. 3. Strengths of the as-pressed composites at different reinforcement concentrations.

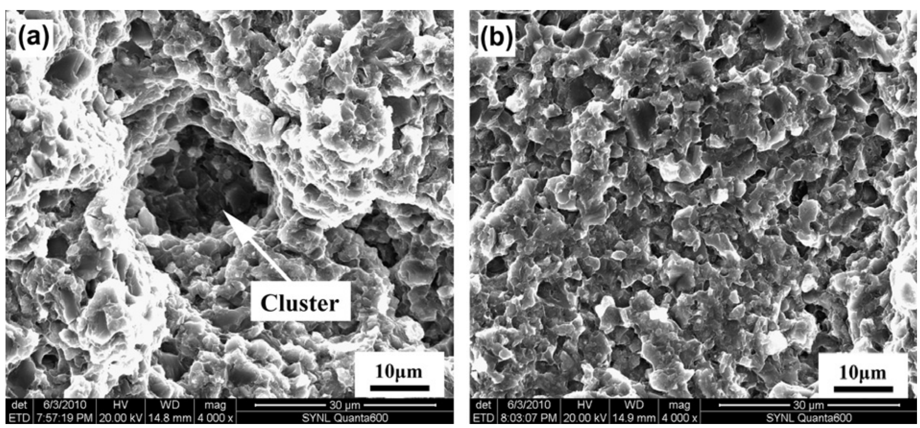

Fig. 4. Fractographs of hot-pressed SiCp/Al composites with different volume fractions: (a) 30 vol.% and (b) 15 vol.%.

SiC showed some large pits due to the SiC clusters, which indicated that the SiC clusters were an important reason for the composite failure.

4. Cluster strength model

4.1. Critical volume fraction of reinforcement

Our previous investigation [10] has built a critical volume fraction model (Fig. 5). Here, we give the equations directly:

$$V_{critical} = 0.27\left(1 - \frac{0.667(D_0/d_0)^3}{\left(1+0.874S^{-2/3}D_0/d_0\right)\left(1+0.874S^{1/3}D_0/d_0\right)^2}\right) \quad (1)$$

$$V_0 = 1 - \frac{0.667(D_0/d_0)^3}{\left(1+0.874S^{-2/3}D_0/d_0\right)\left(1+0.874S^{1/3}D_0/d_0\right)^2} \quad (2)$$

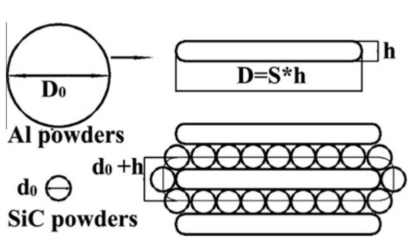

Fig. 5. Schematic of the model for calculations of the $V_{critical}$ and V_0 [10].

where V_0 is the reinforcement concentration when the reinforcements are continuously distributed outside each aluminum particles, $V_{critical}$ is the critical volume fraction of reinforcement, D_0/d_0 is the particle size ratio of aluminum powders to reinforcement powders, and S is the deformation ratio of the aluminum powders.

4.2. Density

When a large amount of reinforcements are added into the aluminum matrix, the clusters will form, which, in turn, affect the properties of the composites. This usually results in the deviation of the actual density of the composites from the prediction by the mixing rule. The experimental measurement of the material density confirms this conclusion (Fig. 2). The higher the concentration of the clusters in the composites, the larger the deviation of the density is.

It should be noted that not all of the reinforcement clusters produced porosity. Some of the clusters could still be filled with the matrix, which commonly happened during the hot-press consolidation or hot-extrusion process. Therefore, the clusters can be divided into two types: (a) the cluster filled with the matrix (referred as non-contacted cluster), which can transfer load at a small strain but lose its ability at a large strain of the tensile history, and (b) the cluster without the matrix filling but with void inside (referred as contacted cluster), which can not transfer load at all.

When the concentration of the SiCp is higher than the $V_{critical}$, the concentration of the cluster is equal to the excess amount of the SiCp. If the cluster is the only reason for porosity, the porosity ratio θ has a linear relationship with the volume fraction of the contacted clusters V_e, which could be calculated assuming that the SiCp are in the closest stacking in the contacted clusters:

$$\theta = (1-K)V_e = (1-K)v(V_p - V_{critical}) \quad (3)$$

where K is the packing factor with a value of 0.74 for the closest stacking of spherical particles [18], v is the ratio of the contacted clusters to the whole clusters, and V_p is the volume fraction of the SiCp.

On the basis of the density measurements, the porosity ratio of the composites could be also calculated using the relation:

$$\theta = 1 - \frac{\rho}{\rho_{Al}(1-V_p) + \rho_{SiC}V_p} \quad (4)$$

where ρ is the measured density of the composite, ρ_{Al} is the theoretical density of the matrix alloy, ρ_{SiC} is the theoretical density of the SiC.

However, the density of the composite could only be measured after the composite has been produced. If we do not get the value of the density, we could estimate the tendency of the contacted cluster ratio for calculation. Two situations should be mentioned here: one is that the contacted cluster ratio is 0 when the reinforcement concentration is smaller than the $V_{critical}$, and the other is that the contacted cluster ratio is 1 when the concentration is larger than the V_0, because this value was obtained based on the situation that the Al particles were completely isolated from each other by the SiCp [10]. The contacted cluster ratio $v = f(V_p - V_{critical})$ increases from zero to one when the V_p increases from the $V_{critical}$ to the V_0. However, the accurate value of v, which depends on the temperature and the pressure, remains unknown. A substitutable treatment is to use the assumed curves to replace the actual contacted cluster ratio. Three possible curves (Fig. 6), corresponding to three different ascent ratios of the contacted cluster ratio, are proposed here to stand for three different filling situations of the clusters: (a) the cluster is filled well, (b) the cluster is filled moderately, and (c) the cluster is filled badly. And their formulas are respectively shown as follows:

$$v = \begin{cases} (V_p - V_{critical})^2/(V_0 - V_{critical})^2 \ (a) \\ (V_p - V_{critical})/(V_0 - V_{critical}) \ (b) \\ 1-(V_0 - V_p)^2/(V_0 - V_{critical})^2 \ (c) \end{cases}, \quad (V_{critical} \leqslant V_p \leqslant V_0) \quad (5)$$

To be specific, if no liquid exists during the PM processing, the cluster is poorly filled by the matrix and curve (c) should be used; if a large amount of liquid is produced during the process, the cluster is well filled and curve (a) should be used. Although the simplification is rough, it is still a method of avoiding the complication and obtaining the approximate change of the non-load cluster ratio.

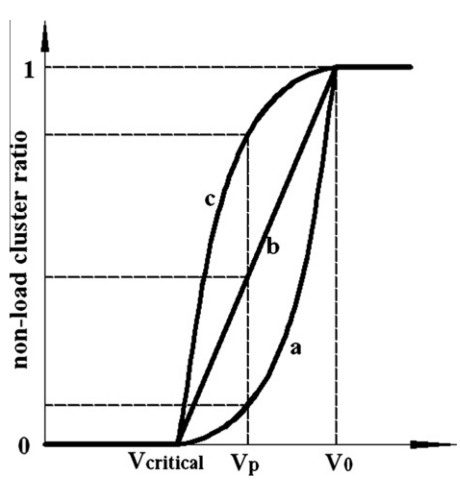

Fig. 6. Schematic of three possible curves of the contacted cluster ratios: (a) the cluster was filled well, (b) the cluster was filled moderately, (c) the cluster was filled badly.

4.3. Strength of composites

Using the modified shear lag model by Wu and Lavernia [14], one could calculate the strength of the composites by dividing the composites into three zones (Fig. 7):

$$\begin{aligned}\sigma_y &= \sigma_p V_p + \sigma_B V_B + \sigma_C V_C \\ &= (\sigma_{m,B} + \Delta\sigma_{int})[V_p(A+2)/2] + \sigma_{m,B}(R^3-1)V_p \\ &\quad + \sigma_{m,C}\left(1 - R^3 V_p\right)\end{aligned} \quad (6)$$

where σ_y is the strength of composites, σ_p is the stress that the particle transfers, σ_B and σ_C are strengths of plastic zone B and elastic zone C in Fig. 7, $\sigma_{m,B}$ and $\sigma_{m,C}$ are the strengths of plastic and elastic matrix zones near the reinforcements, respectively, σ_{int} is the internal stress, R is the ratio of the diameter of the plastic zone to that of the reinforcement, and A is the aspect ratio of particulates.

$$\sigma_{m,C} = \sigma_m + \sigma_{SG} - \sigma_{int} \quad (7)$$

where σ_m is the strength of the matrix material, σ_{SG} is the strength increase due to the refined sub-grains, and σ_{dis} is the strength increase due to the dislocation increasing during quenching.

$$\sigma_{m,B} = \sigma_m + \sigma_{SG} + \sigma_{dis} - \sigma_{int} \quad (8)$$

$$\sigma_{SG} = 90.5D_{SG}^{-1} \quad (9)$$

$$\sigma_{dis} = 1.25Gb\left\{\frac{12V_p\Delta CTE\Delta T}{D_{SiC}b(1-V_p)}\right\}^{0.5} \quad (10)$$

where D_{SG} and D_{SiC} are the sizes of sub-grains and SiCp, respectively, ΔCTE is the difference in the coefficient of thermal expansion between matrix and reinforcement, b is the Burger's vector, and G is the shear modulus of aluminum.

The modified shear lag model could predict the strength of the composites with homogeneously distributed reinforcements. However, clustering is not considered in this model, though the SiC concentration in the PM composites is usually larger than the $V_{critical}$.

Now we consider the contacted clusters, the actual concentration of the reinforcements that could load is $V_p - V_e$, the volume fraction of the plastic zone changes to $(R^3-1)(V_p - V_e)$, and the volume fraction of the elastic zone changes to $(1 - V_e - R^3(V_p - V_e))$. Then, Eq. (6) changes to:

$$\begin{aligned}\sigma_y &= (\sigma_{m,B} + \Delta\sigma_{int})\left[(V_p - V_e)\frac{A+2}{2}\right] + \sigma_{m,B}(R^3-1)(V_p - V_e) \\ &\quad + \sigma_{m,C}(1 - V_e - R^3(V_p - V_e))\end{aligned} \quad (11)$$

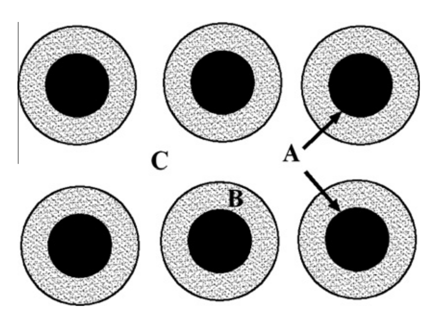

Fig. 7. Schematic of the modified shear lag model by Wu and Lavernia [14]. A – the reinforcement, B – the plastic zone around the reinforcement and C – the elastic zone.

Further, the contacted cluster leads to porosity, which also degrades the strength of the composites. Introducing the influence of porosity in the PM alloys [19,20], the yield strength could be calculated by:

$$\sigma = \exp(-p\theta)\left\{(\sigma_{m,B} + \Delta\sigma_{\text{int}})\left[(V_f - V_e)\frac{A+2}{2}\right] + \sigma_{m,B}(R^3 - 1)(V_p - V_e) + \sigma_{m,C}\left(1 - V_e - R^3(V_p - V_e)\right)\right\} \quad (12)$$

where p is a constant of about 15.5 [19,20].

The calculation of UTS is similar to that of YS, but they still have differences. Cluster induces stress concentration or pore and they are preferentially destroyed at the last moment of the tensile process. Namely, even the non-contacted cluster could not transfer load at that moment. In the condition that the V_p is larger than the $V_{critical}$, the volume fraction of reinforcements which could still transfer load is equal to the $V_{critical}$. And the UTS could be calculated by:

$$\sigma = \exp(-p\theta)\left\{(\sigma_{m,B} + \Delta\sigma_{\text{int}})V_{critical}\frac{A+2}{2} + \sigma_{m,B}(R^3 - 1)V_{critical} + \sigma_{m,C}(1 - (V_p - V_{critical}) - R^3 V_{critical})\right\} \quad (13)$$

5. Discussion

5.1. As-pressed composites

The deformation ratio of the aluminum powders S could be calculated from the inter-layer width of the cold-welded powders in the as-mixed composites based on the constancy volume of the Al powder. The calculated detail could be seen in Ref. [10]. Under this mixing process, it was about 4 according to our previous investigation [10]. Substituting $S = 4$, $D_0/d_0 = 3.7$ into Eqs. (1) and (2) yielded $V_0 = 0.62$, $V_{critical} = 0.17$. As the consolidation temperature was higher than the solidus line temperature, the matrix could be easily densified under the pressure. So the clusters should be the only reason for the porosity.

In the as-pressed composites, the contacted cluster ratio calculated from the density results by Eqs. (3) and (4) are shown in Fig. 8, and these values had a similar tendency with the contacted cluster ratio curve (a) in Eq. (5).

Substituting different V_p values into Eqs. (12) and (13) yields the strength. The strengths predicted by our calculation or the modified shear lag are shown in Fig. 3. R of 1.6 and σ_{int} of 17 MPa were used

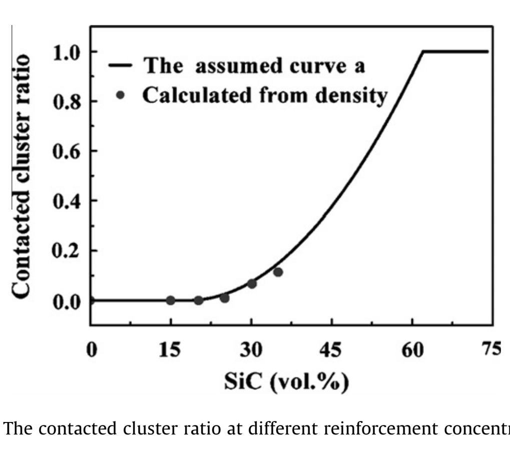

Fig. 8. The contacted cluster ratio at different reinforcement concentrations.

from Refs. [14,21]. G = 26 GPa, b = 0.286 nm, $\Delta\alpha = 2 \times 10^{-5}$ K^{-1} were used from Ref. [22]. Both the modified shear lag and our cluster model could predict well at lower reinforcement concentrations. However, the modified shear lag predicted much larger strength values when the volume fraction of reinforcements exceeded the $V_{critical}$. The cluster model predicted a decrease of strength at higher reinforcement concentrations, which was in agreement with the experimental observations. The YS began to decrease at the concentration of 30 vol.%, which was much larger than the $V_{critical}$, whereas the UTS decreased immediately when the concentration of SiCp was above the $V_{critical}$.

Overall, the cluster model could predict quite well the strength of the composites with the clusters. However, we should note that the UTS values were predicted a little lower. In both the as hot-pressed matrix alloy and composite, the bonding between Al–Al was not strong enough. During the tensile process, the Al–Al weak bonding was another reason for the fracture of the composite. Namely, not all of the clusters in the as-pressed composites were destroyed even at the ultimate tensile moment, deviating from the assumption that all of the clusters would be destroyed, which made the UTS be underestimated.

5.2. As-extruded composites

Under the extrusion condition, the deformation ratio in Eqs. (1) and (2) could be expressed by [10]:

$$S = \gamma^{-3/2} \quad (14)$$

where γ is the extrusion ratio.

Now, we extend the cluster model to the as-extruded composites to check its wide suitability. The experimental data from other researchers [8,23] were used to examine our model. Considering that the influence of the SiCp crack [15] was ignored in our model, we chose only the tensile data of the composite containing relatively smaller SiC particles. Here, the composites with a SiC size of 3 μm and a matrix particle size of 40 μm in Ref. [8] were used. The V_0 and $V_{critical}$ of the composites were calculated to be 0.46 and 0.12 by substituting $D_0/d_0 = 13.3$ and $\gamma = 17.4$ into Eqs. (1), (2) and (14).

Three different types of the ratio of contacted clusters v: curves (a), (b) and (c) were used, respectively. Then, substituting the V_p into Eqs. (12) and (13) yields the strength. The strengths predicted by the model and the experimental data are shown in Fig. 9. The reinforcement size of 3 μm and the quenching temperature of 803 K were used. The YS and UTS of the aged matrix were 297 and 414 MPa, respectively, and the YS and UTS of the solution heat-treated matrix were 151 and 327 MPa, respectively [8]. R of the solution heat-treated and the aged composites were 2.2 and 1.6, respectively [14,21]. The other parameters used in calculation were the same as those in the prediction of the as-pressed composites.

Fig. 9 shows that the calculated strengths using the curve (c) were in good agreement with the experimental strengths under both aged and solutionized conditions. This is understandable. As the composites were fabricated by extruding the cold-pressed powders at 673 K, which was about 100 K lower than its solidus temperature, the filling of aluminum to the reinforcement interspaces was not so complete. Thus, the ratio of the contacted clusters v would quickly increase from zero to one as the reinforcement concentration increased.

A decreasing strength could also be found at a higher concentration of the reinforcements, the peak points of the YS in both aged and solution-treated composites were about 15 vol.%, which was only a little larger than the $V_{critical}$. However, for the as-pressed composites, the content at which the YS began to decrease was

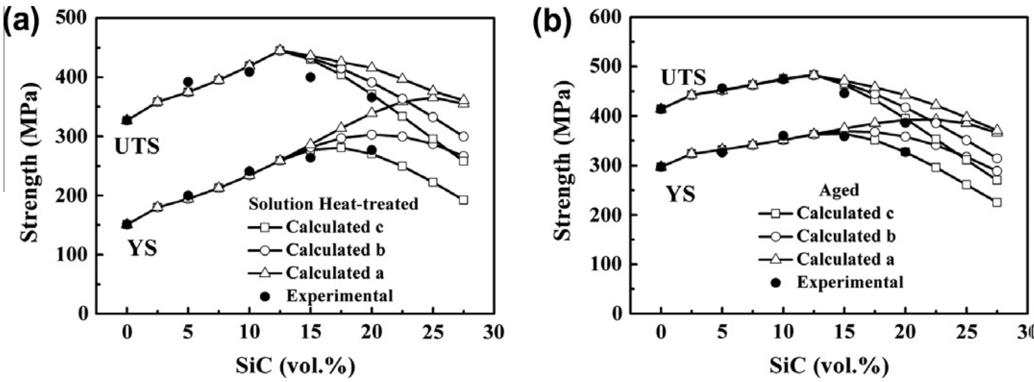

Fig. 9. Strengths of the as-extruded composites at different reinforcement concentrations. (a) As solution heat-treated. (b) As aged. The experimental data were from Ref. [8].

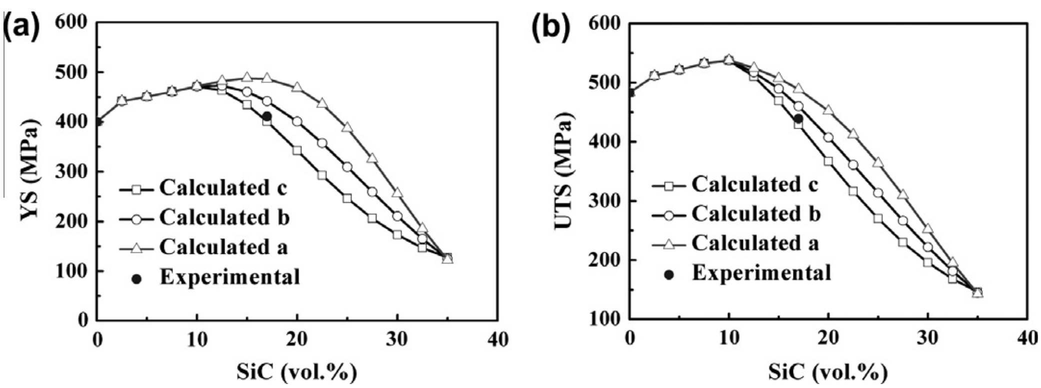

Fig. 10. Strengths of the as-extruded composites at different reinforcement concentrations. The experimental data were from Ref. [23].

much larger than the $V_{critical}$ (Fig. 3). Thus, we could conclude that the existence of the liquid during consolidation could fill the clusters and was beneficial to increasing the strength of the composites.

Furthermore, the tensile data of the composites fabricated by the PM method were taken from Ref. [23]. The V_0 and $V_{critical}$ of the composites were calculated to be 0.347 and 0.0937 by substituting $D_0/d_0 = 19.5$ and $\gamma = 16$ into Eqs. (1), (2) and (14). The YS and UTS of 414 and 483 MPa were used. The reinforcement size was 4 μm and the quenching temperature was 775 K [23]. R of 1.6 was used [14,21]. The other parameters were the same as those used above. As the composite was also fabricated by extruding of the cold-pressed powders and no liquid appeared during the processing, it is understandable to see that the strengths calculated by using the contacted cluster ratio of curve (c) were close to the experimental results (Fig. 10).

Compared with the calculation of the contacted cluster ratio with curve (c) (Figs. 9 and 10), the calculations with curves (a) and (b) had similar tendencies. However, they produced relatively higher strengths, and the concentrations at which the YS began to decrease were moved to higher values. It demonstrates that a good filling of clusters with the matrix could weaken the influences of clusters.

6. Conclusion

1. Clusters in the PM SiCp/Al composites were divided into two types: the contacted cluster and the non-contacted cluster. Based on this division and the critical volume fraction of the reinforcement, a cluster strength model was proposed to calculate the tensile strength of the PM composites with clustering. It is demonstrated that the model could predict the tensile strength in the as-pressed or as-extruded composites well.
2. The model calculations using three different ascent ratios of the contacted cluster ratio demonstrate that a good filling of the clusters, namely the lower ascent ratio of the contacted clusters ratio, could weaken the negative influence of the clusters on the tensile strength, especially the YS.

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