International Journal of Research in Engineering and Science (IJRES)
ISSN (Online): 2320-9364, ISSN (Print): 2320-9356
www.ijres.org Volume 8 Issue 4 ǁ 2020 ǁ PP. 20-25

Densification behaviour and its determination during consolidation processes of Al–SiC metal matrix composites

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ABSTRACT: *The present paper deals with the effect of process conditions on the consolidation in terms of relative density changes concurrent with microstructural evolutions. Powder metallurgy and vacuum hot pressing were used for the development of SiC-particle reinforced aluminum metal matrix composites. Increasing temperature or pressure led to increased densification rates. Applied pressure, however strongly influenced densification time for the materials. Levels of consolidation together with mechanical properties of the developed products also depended on the volume fraction of reinforcement particles. A constitutive model is presented to determine the densification behavior of the materials. The model was implemented into finite element software so process simulations could be carried out and the predicted relative density could be compared to experimental observations.*

Keywords: *Metal matrix composites (MMCs); Powder metallurgy; Vacuum hot press; Consolidation behavior; Relative density*

I. INTRODUCTION

SiC-particle reinforced aluminum matrix composites have been studied often due to their strength, stiffness, and ware resistance for a range of applications [1,2]. Recently, several fab-rication techniques, including liquid and solid state processes, have been developed for particle reinforced metal matrix com-posites (MMCs). Even though solid state production costs are relatively higher than usual liquid casting processes, MMCs that are produced with a solid state process exhibit excellent fin-ished performances [3]. Powder metallurgy (PM) followed by compaction or sintering is a common solid state manufacturing technique. In addition, vacuum hot pressing (VHP) can enhance the sintering rate by providing additional stress at elevated tem-peratures. In accordance with the ability to obtain a uniform distribution of reinforcement and near net-shape formability, it is possible to use the processes efficiently [4].

Generally, PM involves blending matrix alloy with reinforce-ment particles and performing a solid state sintering process. When consolidating a powder to develop a desired-shape, den-sification occurs by mechanisms, such as diffusion, plastic flow, and power-law creep [5]. In addition to these mecha-nisms, microstructural changes occur due to thermal effects and non-uniform stress concentrations under hot pressing. As discussed in Ref. [6], the densification models for porous media may be classified into two different types: micro- and macro-approaches. In the micro-approach, the mechanisms of densification can be analyzed in a single particle point of view. The changes of relative density against temperature or pres-sure thus can be predicted by means of the corresponding mechanisms-based densification rate equations. In the macro-approach, the porous materials are considered as continuum media. Constitutive equations for the porous media can there-fore be formulated by revising the general plasticity theory for solid materials.

To ensure that the models developed are general in nature, it is necessary to provide accurate constitutive equations enabling the macro- and micro-approaches to be coupled in order to well represent the physical processes [6]. In addition, the criteria for the determination of the processing conditions are particularly important because the applied conditions or material-associated factors can contribute to failure of the mate-rials or inadequate densification. This is the aim for the present paper. SiC-particle reinforced aluminium-MMCs were devel-oped, using powder metallurgy and vacuum hot pressing. The effects of the processing conditions on consolidation and the

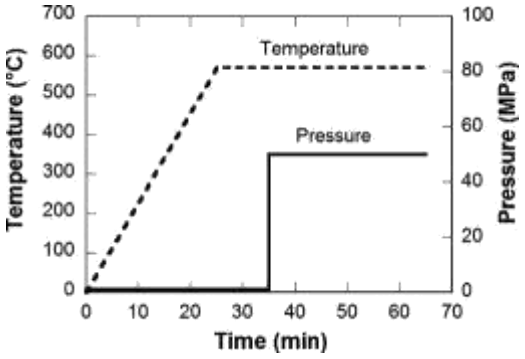

Fig. 1. Consolidation cycles for VHP test.

microstructural evolutions of the matrix materials were investi-gated. A unified densification model was developed based on the micro-mechanics framework for porous plastic materials. The relationships of the different processing conditions and the evo-lutions of porosity with its subsequent properties were analyzed and compared with the experimental data.

II. EXPERIMENTAL INVESTIGATIONS

Al6061 matrix alloy and SiC-particulate reinforced compos-ites were consolidated, using general powder metallurgy and vacuum hot pressing. To investigate densification behavior, dif-ferent sets of consolidation cycles were applied to reach the fully dense state. Several of the tests were interrupted at various stages of consolidation so microstructural evolutions could be examined. Fig. 1 shows a typical consolidation cycle.

The process used for the development of Al-MMCs is found elsewhere but is summarized here [4]. Using a tubular mixer, the gas-atomized, −325 mesh (less than 45 mm) Al powders were blended in an alcoholic solvent with SiC-particles at an average diameter of 11 mm. The mix was dried in air. Before consoli-dation, the blended powders were positioned within the die to achieve the initial relative density of 0.6. A final vacuum, on the order of 10^{-4} to 10^{-5} Torr, was pulled after the purge, and then 10^{-3} Torr was maintained during the process. By adjust-ing the auto-controlled power of the induction heat system, the mixed powders were hot pressed at 490–570 °C under pressures of 50–70 MPa. For all of the tests, an initial load of 0.2 MPa was applied to provide a high uniform static load. After consol-idation, the specimen was allowed to furnace cool. The usual post-processing was performed to quantify microstructural fea-tures. Similar subsequent experiments were conducted for the development of Al-powder-only specimens so that the defor-mation behaviors of the matrix materials could be investigated. Fig. 2 shows the microstructure of the composites obtained at the intermediate stage of consolidation process. The chemical compositions of the Al6061 matrix material and SiC-particles are shown in Tables 1 and 2, respectively.

III. MODELING THE DENSIFICATION OF AL-MMCS

The matrix material Al6061 exhibited a rate-dependent elasto-viscoplastic behavior at high temperatures during the con-

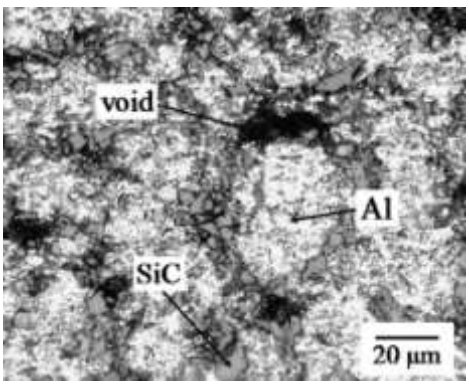

Fig. 2. Microstructure of Al6061–30 vol.% SiC composites with the relative density of 0.85.

Table 1
Chemical composition of Al6061 powder (wt.%)

Mg	Si	Fe	Cu	Mn	Cr	Zn	Ti	Al
1.0	0.61	0.1	0.28	0.08	0.18	0.05	0.05	Remaining

solidation. The mechanisms-based constitutive equations for both Al and Ti alloys are presented in a previous work [7]. These equations were implemented into the modeling of the consolidation behavior of Ti-MMCs [8].

Let Internal nal stress, $\bar{\sigma}_y$ the yield stress, $\dot{p}$ the effective plastic strain rate, d the mean grain size, and α, β, γ , C_1, γ_1, α_1, β_1 and μ are material-dependent parameters. Eq. (1) relates the plastic strain rate to the net stress. Eqs. (2) and (3) account for the isotropic hardening and grain growth kinetics, respectively. To determine the deformation behavior of matrix materials and the parameters included in the equations, tensile tests were performed, using a standard uniaxial specimen obtained from the consolidation pro-cess. Experimentally measured stress–strain behaviors, together with corresponding grain size against time were used. During the tests, the crosshead speed was programmed to increase with specimen elongation to maintain a constant strain rate. Compu-tational procedures were developed for the determination of the material parameters, and a minimization method was used. The procedures are found elsewhere [7]. By employing the tensile test data reported in literature [9] and obtained by the author, the

Table 2
Chemical composition of SiC-particle (wt.%)

SiC	SiO2	Si	Fe	Al	C
98.5	0.5	0.3	0.08	0.1	0.3

Table 3
Material parameters for Al6061 at 550 °C

α	β	γ	C_1	γ_1	α_1	β_1	μ
0.28 × 10^{-4}	0.73	0.56	19.9	4.91	0.13×10^{-9}	0.45×10^{-6}	0.2

material parameters determined for Al6061 at 550 °C are given in Table 3.

During consolidation, internal pores were removed at an ele-vated temperature under applied pressure. By using the modified Gurson models [8–12], the flow potential function for a porous plastic material can be written as [8]:

$$\Phi = \frac{\sigma_e^2}{\bar{\sigma}^2} + 2p_d f \cosh\left(\frac{\sigma_m}{2\bar{\sigma}}\right) - 1 - p_d^2 f^2 \qquad (1)$$

where f is the volume fraction of voids, σ_e the effective stress of the porous material, $\bar{\sigma}$ the flow strength of the matrix mate-rial, σ_m the mean stress of the porous material, and p_d and p_m are geometry-associated parameters. As discussed in the Wang model [13], the exponential form for p_m is given to fol-low the accurate densification behavior for the powder-based matrix material.

IV. RESULTS AND DISCUSSION

Fig. 3 shows the temperature-dependent relative density changes with time under 30 MPa of pressure. The temperature dependence of the rate of deformation can be described by the Arrhenius equation, and this approach to the experimental data enabled the material parameters to be calculated. It shows that the densification rate increased as temperature increased. Gen-erally a reasonable qualitative agreement was achieved between experimental and model predictions. The temperature depen-dence of flow stress has been widely studied for the materials [14]. For the case of relatively low temperature range, as shown in Fig. 3, dislocation creep dominates the deformation process.

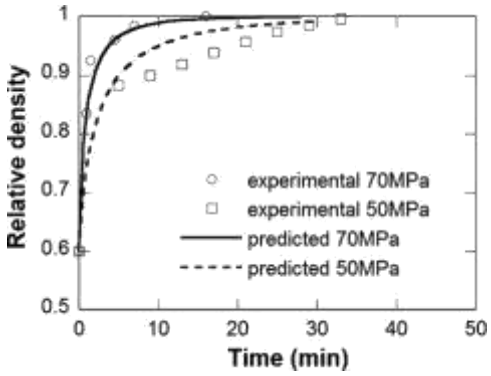

Fig. 3. Variations of relative density for two temperatures under 30 MPa. under 30 MPa at 570 ° C.

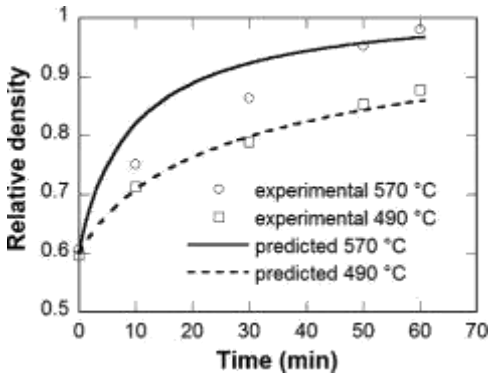

Fig. 4. Variations of relative density for two pressures at 570 ° C.

In the high temperature range, however grain boundary slid-ing is associated with the deformation mechanism providing rapid densification with relatively lower flow stresses. In the mean time, the rate of densification decreased as consolida-tion increased. At the later stages, therefore more time was required to reach the fully dense state. The possible mecha-nism may be explained by means of porosity evolution such that the fine pores at the particle interfaces have prevented the progress of densification. Fig. 4 shows a comparison of den-sity evolution with time for different pressures. Increasing the pressure reduced the time it took to reach full density. By com-parison with the results between temperature and pressure, the applied pressure had a stronger influence on the densification rate for the materials than temperature. Using the same pro-cessing conditions of temperature and pressure but different volume fractions of reinforcement, evolutions of relative den-sity are shown in Fig. 5. Low volume fractions of reinforcement led to higher densification rates so as to the matrix-only mate-rial without reinforcement considerably reduced consolidation time. Both the processing conditions and the material-dependent characteristics are important for the consolidation of powder mixtures [15]. Either relatively small sizes of reinforcement than matrix powder or high volume fractions of reinforcement exhibit more consolidation time by the continuing increment of micro-voids with increased flow stress during the processes. In order to determine the effect of volume fraction of reinforcement on mechanical behavior, further tensile tests were performed using

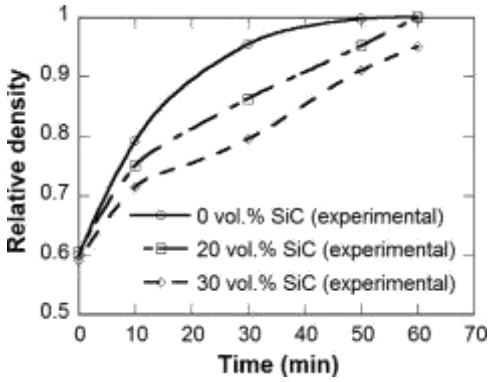

Fig. 5. Variations of relative density for three reinforcement volume fractions

Table 4
Effect of SiC volume fraction on tensile properties of Al–SiC composites consolidated at 570 ° C under 30 MPa

SiC (11 mm) vol.%	Young's modulus (GPa)	Yield strength (MPa)	U.T.S (MPa)	Elongation (%)	Relative density
20	79	131	218	5.8	1.0
30	99	192	259	2.3	0.987

the composites developed. Test pieces with a gauge length of 20 mm were subjected to uniaxial constant velocity loading of 0.2 mm/min until failure. Experimentally measured tensile prop-erties are given in Table 4. As can be seen, 10% difference of SiC volume fraction results in approximately 30% change of tensile properties of Al-MMCs. Elastic modulus, yield strength, and ultimate tensile strength increased as increasing reinforcement. The increasing SiC volume fraction, however leads to decreas-ing elongation, and the reasons may be considered by either drop of ductility due to the hard reinforcement particle or the effect of micro-voids with subsequent coalescence during the deformation. Similar trend was observed in Ref. [4].

V. CONCLUSIONS

Experimentally measured densification behaviors under vari-ous processing conditions, together with powder characteristics, were compared to model predictions. Increasing the temperature or pressure led to increased densification rates. Applied pres-sure, however reduced densification times more than increasing the temperature did. In addition to the processing conditions, powder characteristics also influenced the evolution of relative density with subsequent mechanical properties of the developed composites. The materials with higher volume fractions of rein-forcement required more consolidation time to reach the fully dense state due to increased flow stress during deformation, and 10% difference of SiC volume fraction results in approximately 30% change of tensile properties. Thus, knowledge of both the processing conditions and the material characteristics are essen- tial in the determination of the level of consolidation. A method was presented to achieve this.

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