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Original Article

Studies on formability of sintered aluminum composites during hot deformation using strain hardening parameters

*Sumesh Narayan**, *Ananthanarayanan Rajeshkannan*

Mechanical Engineering, School of Engineering and Physics, Faculty of Science, Technology & Environment, The University of the South Pacific, Laucala Campus, PO Box 1168, Suva, Fiji

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A B S T R A C T

Formability is the limit to which a material can be deformed before failure and is upmost importance in powder metallurgy (PM) forming process. This is because the presence of porosity in the PM part after the sintering process. In this study two key strain hardening parameters are used to study the workability behavior or determining the failure zone. This can be used for design of PM parts and most importantly the die design as repressing needs to be employed before pores appear as cracks on the free surface. It is nearly impossible to produce defect free parts if this failure occurs. The hot formability behavior of aluminum metal matrix composites (MMC's) that is, Al-4TiC, Al-4WC, Al-4Fe_3C and Al-4Mo_2C (by weight percentage) are presented in this paper.

1. Introduction

The forming limit of PM compacts is absolute important and the study of workability behavior of PM materials is an essential study in designing of the deformation process [1,2]. Workability of the PM compacts plays a key part to find out if the PM compact is shaped effectively or fracture starts during the deformation process. Workability is the amount of deformation and induced internal stresses a material can handle during upsetting prior to failure and depends on a number of deforming factors such as stress and strain rate, friction, temperature and material [3,4]. Several constitutive equations have been developed to appreciate the constitutive performance of PM parts during hot forming processes [5–7]. Further, formability stress factor (β) is proposed in [3] which describe the consequence of hydrostatic and equivalent stresses during the forming process. The authors have used the models developed earlier by Kuhn-Downey [8] and Whang-Kobayashi [9] and also studied the influence of density on formability behavior of PM parts during forming. During the forming process several fracture behavior is present that depends on the amount of triaxiality [10,11].

Shima and Oyane [12] and Green [13] studied workability (formability stress index and mean stress) and densification behavior looking at several round pores, axial stress and ini-

* *Corresponding author*.
E-mail: narayan_su@usp.ac.fj (S. Narayan).

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tial theoretical density. Narayansamy et al. [14–16] presented the fracture mechanisms of PM parts in three different stress states, that is, plane, uniaxial and triaxial. Further, the authors have studied the technical relationship that exists between the hoop, mean and effective stresses against deformation and densification. Vujovic and Shabaik [17], Doraivelu et al. [18] and Ko et al. [19] suggested a novel forming limit measure for PM material confirming with experimentations and numerical works all based on formability stress index, hydrostatic and equivalent stress. The present investigation proposes to study the workability behavior by studying the strain hardening parameters, strain hardening exponent (ni) and stress coefficient (Ki). Several investigators studied strain hardening behavior to evaluate the densification and strain hardening behavior, however, hardly any research was conducted to find the forming limit using the two very important strain hardening parameters. The strain hardening coefficient and the stress coefficient are one of the basic forming constraints of metal matrix composites. Strain hardening studies are vital in the deformation process as it governs the extent of even plastic strain the metal can sustain throughout the deformation without failure.

Narayanasamy et al. [4] explored on the instant strain-hardening performance of a PM aluminum-iron alloy. The effect of various iron content and preform geometry on strain hardening and densification were established. Luo et al. [20] studied the influence of temperature, strain rate and strain on strain hardening. Further, a correlation between strain hardening parameters (ni and Ki) with axial strain and relative density was developed experimentally and used to evaluate the geometric and matrix work hardening [21,22]. An interesting point to note from these researches [20–22] is that during the initial stages the strain hardening increases rapidly and then decreases sharply. This behavior is due to large degree of deformation during the initial stages of deformation and needs to be neglected for all practical reasons. Then the strain hardening values maintain a steady behavior and finally during the last phase of forming there is fluctuation in the strain hardening values. This final stage can be analyzed to plot the forming limit diagram and determine the failure zone. The sintered forging process is widely used in industries for producing parts with uniform properties and complex geometry. Further, one of the quests today is producing high strength materials using green manufacturing such as PM manufacturing process.

The paper analyzes the formability limit of PM preforms of Al-4TiC, Al-4WC, Al-4Fe_3C and Al-4Mo_2C experimentally with the influence of preform geometry, initial relative density and various carbide reinforcements. The instantaneous strain hardening (ni) and instantaneous stress coefficient (Ki) is used to plot the forming limit diagram.

2. Materials and method

2.1. Materials

Nowadays, numerous investigators are working on producing frontier materials that will benefit our society in one way or another. Aluminum MMC's are in demand for industrial applications due to some very good properties, main one being high strength to density ratio [23,24]. Carbide reinforced aluminum are widely used as carbide particulate are good in wear and corrosion resistance, high strength and hardness. Hence, in this research work several aluminum MMC's are prepared using PM process and forming limit in investigated using the strain hardening parameters. Aluminum powder (150 μm in diameter) and carbide powders (50 μm in diameter) were used to prepare titanium carbide reinforced aluminum, tungsten carbide reinforced aluminum, molybdenum carbide reinforced aluminum and iron carbide reinforced aluminum composites for this study. The sieve analysis and basic characterization of aluminum powder and the corresponding composition was completed by standard procedures and given in Tables 1 and 2, respectively.

2.2. Experimental method

Required amount of powders were taken to prepare blends of the aforementioned compositions in a planetary ball mill, model Retsch PM400MA. The mixing process was conducted for 2 h at a speed of 200 rpm. The homogenous mixture was ensured by taking the apparent density and required intervals. The required amount of powders to produce Al-4TiC, Al-4WC, Al-4Fe_3C and Al-4Mo_2C with height-to diameter ratios (aspect ratio, AR) of 0.4 and 0.6 were compressed using a hydraulic press. The load was varied from 139 MPa to 159 MPa so that to achieve relative densities of 0.82 and 0.86. To prevent oxidation during the sintering process, these compacts were then covered with ceramic paste as described elsewhere [22] and were left for atmospheric drying for a period of 12 h and then at 220 °C for a period of 30 min in an electrical muffle furnace. Finally, the temperature was increased to 594 °C for the sintering process which further took 60 min.

Hot upsetting under dry friction condition was carried out at the sintering temperature to obtain various height strains until visible cracks can be seen on the free surface. Then all the compacts were left in atmospheric conditions to cool to room temperature after which dimensional measurements were taken to determine axial strain, effective strain, effective stress, hydrostatic stress, formability stress index, instantaneous stress coefficient and instantaneous strain hardening coefficient. Furthermore, Archimedes technique was used to determine the compact densities. The maximum deformed and undeformed specimens of each composition were cut into two halves and microstructural views were obtained at the diametrical end (near the edge).

2.3. Yield criteria

The following equation is used by many investigators [2,15]:

$$AJ_2^{/} + BJ_1^2 = Y^2 = \delta Y_0^2 \quad (1)$$

Further, J_1 and $J_2^{/}$ in the cylindrical coordinate and for axisymmetric forging, $\sigma_r = \sigma_\theta$, is given by [15]

$$J_1^2 = 4\sigma_\theta^2 + \sigma_z^2 + 4\sigma_\theta\sigma_z \quad (2)$$

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