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Achieving a desirable combination of strength and workability in Al/SiC composites by AHP selection method

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ABSTRACT

Aiming the selection of an Al/SiC composite with best combination of strength and workability, the analytical hierarchy process (AHP) method was applied. Several composites produced for a certain purpose, through powder metallurgy routes having different manufacturing parameters such as size and fraction of reinforcement, milling time and relative density were ranked by AHP method. The instantaneous density coefficient (A_i), instantaneous strain-hardening exponent (n_i) and formability stress index (β) were measured under triaxial stress state conditions. AHP results revealed that Al/10 wt.%SiC (16 μm) with relative density of 95% and milled for 12 h, was the preferred composite material. It was also concluded that the relative density of the composite was the most significant property which may affect the mechanical properties of the material.

1. Introduction

Metal matrix composites (MMCs) are engineering materials in which a hard ceramic component is dispersed in a ductile metal matrix in order to obtain characteristics that are superior to those of the conventional monolithic metallic alloys [1]. It is well known that metal matrix composites (MMCs) exhibit a significant improvement in mechanical performance over unreinforced alloys in many commercial structural applications and can be substitute the conventional structural alloys [2–4]. In the last 10 years, a number of MMCs have appeared, which use ceramic particles as reinforcement in pure aluminum or an aluminum alloy [1].

Aluminum-matrix composites reinforced with hard ceramic particles are relatively easy to process and, in comparison with fiber-reinforced composites, are nearly isotropic [5]. SiC, is among the widely used ceramics due to its low cost as reinforcement in aluminum [6]. The performance of these materials under compressive loading has received only minor attention, in spite of the fact that these materials have great potential in fields such as aviation and automotive components, where knowledge of the compressive characteristics is essential [1]. Furthermore a wide range of production techniques have been developed for aluminum matrix composites. However, the powder metallurgy (P/M) is the most attractive techniques since it gives good mechanical properties and is an inexpensive process [5,7]. Therefore, it seems crucial to find out the compressive and deformation behavior of the MMCs which produced by P/M. Several research works have focused on the workability and deformation studies on cold upsetting of Aluminum composites [8–10].

Comparing candidate materials, ranking and choosing the best material is one of the most important stages in material selection process [11,12]. It must be noted that in some cases, there is more than a single definite criterion for selecting the right kind of material. The designers and engineers have to take into account a large number of material selection criteria. There is a need for a simple, systematic and logical scientific method or mathematical tool to guide designers in taking a proper material selection decision. Using linear assignment method, the multi-criteria decision making (MCDM) approach is proposed in decision-making process to rank the materials for a given engineering component with respect to several criteria. The proposed material selection procedure is relatively simple. In material selection for properties that can be represented by numerical values, the multi-criteria decision making (MCDM) methods have been used prevalently [13] The Analytic Hierarchy Process (AHP), introduced by Saaty [14] is one of the most frequently discussed methods of MCDM and have a high potential to solve material selection problems. It has proven to be an extremely useful decision-making method. The reason for AHP's popularity lies in the fact that it can handle the objective as well as subjective factors, and the criteria weights and alternative scores are elicited through the formation of a pairwise comparison matrix, which is the heart of the AHP [15].

The present study is aimed to propose a systematic assessment model for determining an optimal condition in order to obtain the

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best compression and deformation properties of Al–SiC composites produced by PM with the aim of AHP method.

2. Theoretical foundations

2.1. Workability of powder metallurgy composites during cold upsetting

Metal working processes involve plastic deformation that results in the change of both the cross-sectional area of the work piece and of its overall shape. Different metal working processes produce different stress states during deformation. Bulk metal working processes produce a state of stress that is generally triaxial with the major stress components being compressive. When one of the stress components becomes tensile at some points in the deformation region, fracture is the limiting factor for these processes.

The plastic deformation of powder preform material is similar to that of conventional materials, but is complicated by the effect of a substantial volume fraction of voids in the material. In addition to volume change, yielding of porous metals is also not completely insensitive to the hydrostatic stress imposed. During the upsetting of metal powder preforms the mode of deformation is quite different from that of wrought materials and is function of the both density and the hydrostatic stress [16]. The mathematical expressions used for the determination of various upsetting parameters of upsetting of powder preform material are discussed below.

2.2.1. Formability stress index

Kuhn and Downey [17] determined the basic deformation and fracture behavior of sintered powder materials through the use of the simple compression test, establishing that densification can be enhanced and fracture can be delayed by increasing the compressive level of stress on the material. The plastic Poisson's ratio (v) was obtained for sintered powder compacts in homogeneous compression for both hot- and cold-working for ferrous and non-ferrous powders found to be given by

$$v = 0.5\rho^2 \tag{1}$$

where ρ is the density of preform.

According to Narayanasamy et al. [18] the state of stress in a triaxial stress condition is given by

$$v = \frac{(2+R^2)\sigma_\theta - R^2(\sigma_z + 2\sigma_\theta)}{(2+R^2)\sigma_z - R^2(\sigma_z + 2\sigma_\theta)} \tag{2}$$

where v is Poisson's ratio, R is relative density, and σ_z and σ_θ are axial and hoop stress components respectively. From Eq. (2), the hoop stress component can be determined by [19]

$$\sigma_\theta = \left(\frac{2v + R^2}{2 - R^2 + 2R^2 v}\right)\sigma_z \tag{3}$$

The hydrostatic stress is given by [19]

$$\sigma_m = \frac{\sigma_z + \sigma_r + \sigma_\theta}{3} \tag{4}$$

In the case of axisymmetric triaxial stress condition, the hoop and the radial stresses are equal ($\sigma_r = \sigma_\theta$). Therefore, Eq. (4) can be rewritten as follow [19]:

$$\sigma_m = \frac{\sigma_z + 2\sigma_\theta}{3}. \tag{5}$$

As discussed in [19,20] the effective stress (σ_{eff}) can be determined as follow:

$$\sigma_{eff} = \left[\frac{\sigma_z^2 + 2\sigma_\theta^2 - R^2(\sigma_\theta^2 + 2\sigma_z\sigma_\theta)}{(2R^2 - 1)}\right]^{0.5} \tag{6}$$

As an outgrowth of experimental evidence of the importance of the hydrostatic component of stress state on fracture, Vujovic and Shabaik [21] proposed a parameter called a formability stress index 'β' which can be calculated by

$$\beta = \left(\frac{3\sigma_m}{\sigma_{eff}}\right) \tag{7}$$

This index determines the fracture limit as explained by Vujovic and Shabaik [21].

2.1.2. Instantaneous strain-hardening exponent and instantaneous density coefficient

During upsetting, the axial true strain (ε_z) is expressed as:

$$\varepsilon_z = \ln\left(\frac{h_0}{h_f}\right) \tag{8}$$

where h_0 and h_f are initial and final heights of preform.

As explained by Narayansamy and Pandey [22], the hoop strain (ε_θ) can be determined by:

$$\varepsilon_\theta = \ln\left(\frac{2D_b^2 + D_c^2}{3D_0^2}\right) \tag{9}$$

where D_0 is the initial diameter, D_b is the bulged diameter and D_c is the average contact diameter. By considering the top and bottom contact diameters as D_1 and D_2 respectively, the average contact diameter (D_c) can be calculated by following expression [22]:

$$D_c = \frac{D_1 + D_2}{2} \tag{10}$$

In the case of triaxial stress state condition, the radial strain is equal to hoop strain, so, the effective strain is given by Narayanasamy et al. [19] as below:

$$\varepsilon_{eff} = \left\{\left(\frac{2}{3(2+R)}\right)\left[(\varepsilon_z - \varepsilon_\theta)^2 + (\varepsilon_\theta - \varepsilon_z)^2\right] + \left(\frac{(\varepsilon_z + 2\varepsilon_\theta)^2}{3}\right)\left[1 - R^2\right]\right\}^{0.5} \tag{11}$$

For theoretical computations, it is often necessary to represent an experimentally determined stress–strain curve by an empirical equation of suitable form (constitutive relationships). When the cold deformation is sufficiently large for the elastic strain to be neglected, it is frequently convenient to employ the Ludwik power law [23]:

$$\sigma_{eff} = K\varepsilon_{eff}^n \tag{12}$$

where K is strength coefficient and n is a strain-hardening exponent usually lying between 0 and 0.5. Effective stress and strain can be calculated by Eqs. (6) and (11) respectively. For compressive materials (i.e. metal powder preforms) the strength coefficient relates to relative density by the following expression:

$$K = K_1 R^A \tag{13}$$

where A is the density coefficient [10].

Assuming that the consecutive compressive loads were specified as 1, 2, 3,..., ($m-1$), m, it was proved elsewhere [19] that the instantaneous strain-hardening exponent (n_i) can be obtained by

$$n_i = \frac{\ln(\sigma_m/\sigma_{m-1})}{\ln(\varepsilon_m/\varepsilon_{m-1})} \tag{14}$$

Also, the instantaneous density coefficient can be calculated by [10]:

$$A_i = \frac{\ln(\sigma_m/\sigma_{m-1})}{\ln(R_m/R_{m-1})} \tag{15}$$

2.2. Analytical hierarchy process (AHP)

AHP, developed by Saaty addresses how to determine the relative importance of a set of activities in a multi-criteria decision problem [24]. The AHP provides a comprehensive and rational frame-work for structuring a decision problem for representing and quantifying its elements, for relating those elements to overall goals and for evaluating alternative solutions [25]. The general idea in the AHP method is to make the pairwise comparisons, both of the alternatives with respect to the criteria (scoring) and criteria with respect to themselves to estimate the criteria weights (weighting) [26]. AHP is a widely used multi-criteria decision making tool due to its simplicity, ease of use and great flexibility [27]. The AHP method is based on three principles: first, structure of the model; second, comparative judgment of the alternatives and the criteria; third, synthesis of the priorities [25,28–30].

2.2.1. Construction of the hierarchy

In the first step, a complex decision problem is structured as a hierarchy. AHP initially breaks down a complex multi-criteria decision-making problem into a hierarchy of interrelated decision elements (criteria, decision alternatives). With the AHP, the objectives, criteria and alternatives are arranged in a hierarchical structure similar to a family tree.

2.2.2. Priority setting

The second step is the comparison of the alternatives and the criteria. Once the problem has been decomposed and the hierarchy is constructed, prioritization procedure starts in order to determine the relative importance of the criteria within each level. The pairwise judgment starts from the second level and finishes in the lowest level, alternatives. In each level, the criteria are compared pairwise according to their levels of influence and based on the specified criteria in the higher level. In AHP the pair comparison is developed assigning values from 1 to 9 to express the level importance in the decision of the two element properties. Table 1 displays the meaning of the comparison scale used in the weighting of two elements [28].

The result of the pairwise comparison developed inside the AHP on "n" criteria is applied to provide a reciprocal ($n \times n$) evaluation matrix $A = \{a_{ij}\}$.