Materials Science and Engineering A 458 (2007) 48–57

MATERIALS SCIENCE & ENGINEERING A

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Numerical simulation of laser forming of aluminum matrix composites with different volume fractions of reinforcement

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Received 5 January 2006; received in revised form 8 December 2006; accepted 11 December 2006

Abstract

In this paper, the deformation behavior of an aluminum matrix composite with different volume fractions of particle reinforcement was investigated during laser forming by a microstructure-integrated finite element method. A modified self-consistent analytical model was developed to obtain the relationship between the mechanical properties of the composite and its matrix material. Different from Duva's model, the present analytical model assumed that the matrix material and the composite follow the same Ramberg–Osgood type of power law but with different hardening exponents. Based on the properties of the matrix material determined by the analytical model, the thermo-physical properties of the composite with different volume fractions of particles were obtained by the unit cell model. A microstructure-integrated finite element method was subsequently applied to predict the deformation behavior and the bending angle of the composite. It was found that the bending angle of the composite increased with an increase in volume fraction of particles.

Keywords: Laser forming; Metal matrix composite; Analytical model; Finite element model

1. Introduction

Since 1986, laser forming has emerged as a hot working process to deform work pieces using thermal stress induced by laser irradiation. A considerable number of experimental and numerical investigations were carried out to understand the process over the past decades. Vollertsen proposed three mechanisms, the temperature gradient mechanism (TGM) [1], the buckling mechanism (BM) [2] and the upsetting mechanism (UM) [3]. Based on the mechanisms, some analytical models were developed to predict the bending angles by laser forming [4–6]. In order to broaden the applications of the technology, some irradiation strategies were performed to obtain the complicated shapes (dome or saddle) of work pieces by laser forming [7], and a considerable number of materials including low or mild carbon steel [8], ceramics [9], high strength steel [10], chromium [11] and titanium alloy [12] were examined. Meanwhile, with the development of the computer technology, a number of researchers have applied numerical methods to simulate the process [13–15].

Although laser forming has been investigated quite extensively, most of the experimental and theoretical work still focuses on monolithic alloy. Chan and Liang [16] have experimentally demonstrated that an aluminum matrix-based composite (Al6013) can be deformed to a large angle by laser irradiation. Liu et al. [17] proposed an analytical model to predict the deformation of the composite. Very recently, Liu et al. [18] have further attempted to simulate the thermo-mechanical process by the finite element method integrated with the unit cell model, by which the properties of a composite can be obtained in terms of the properties of the matrix and the reinforcements. It shows that the deformation behavior of metal matrix composites during laser forming is greatly affected by the mechanical properties of their matrix materials. As it is relatively difficult to obtain the true mechanical properties of a matrix material in a composite, a substitutive approach has been used to obtain the properties from the experimental results of the composite through an analytical model. Quite a few analytical models [19–24] have been developed to describe the relationship between a composite and its matrix/reinforcement. Following the Eshelby ellipsoidal inclusion theory (1957) [19], the analytical models such as Mori–Tanaka model [20], the self-consistent model [21] and the differential model [22] are based

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doi:10.1016/j.msea.2006.12.110

on the medium field concepts, which assume that the stress and strain fields in the matrix and in the reinforcement are adequately represented by averaging the volume fraction of them in the elastic regime, although they are different in the way that they account for the elastic interaction between the phases. The models were then extended to plastic regime by using the tangent [23] or secant formulations [24] to build up the relationship of the stress and strain through the overall elasto-plastic deformation. Another approach developed by Christensen and Lo [25] assumed that a kernel consisting of a spherical inclusion was surrounded by the matrix layer, which was in turn embedded into the effective medium. Based on the self-consistent method, Duva introduced a model to depict the random distribution of rigid spherical particles bonded in a power law matrix following the same work hardening exponent as the composite [26]. Bao et al. further extended this model to study the overall limit flow stress for composites with randomly orientated disc-like or needle-like particles [27].

In this paper, a modified self-consistent analytical model with consideration of the different work hardening behavior of the matrix and the composite is proposed to represent the relationship between the mechanical properties of the composite and its matrix. Based on the predicted properties of the matrix, the thermo-mechanical properties of the aluminum matrix composite will be predicted by the unit cell model. They will then be used to simulate the deformation behavior of a MMC with different volume fractions of reinforcement during laser forming by a microstructure-integrated finite element method.

2. Analytical model

In the analytical model, the matrix material is assumed to be incompressible. The inclusions behave elastically in all loading conditions and their stiffness is much higher than that of the matrix so that the inclusion can be regarded as being rigid. Damages of the composite including porosity, reinforcement fracture, interface debonding and matrix cracking are not accounted for in the present model. The stress and strain relationship of the composite is assumed to follow the Ramberg–Osgood type of power law:

$$\varepsilon_c = \frac{\sigma_c}{E_c} + \alpha\varepsilon_0\left(\frac{\sigma_c}{\overline{\sigma_r}}\right)^{\overline{N}} \quad (1)$$

where $\bar{N} = 1/\bar{n}$, σ_c and ε_c the uniaxial stress and strain of the composite, respectively, E_c the Young's modulus of the composite, the coefficient α is taken to be 3/7 by Ramberg and Osgood, and ε_0 is the yield strain of material. $\overline{\sigma_r}$ is the asymptotic reference stress, which will converge to a constant with sufficiently large strain. When the deformation approaches the elastic-perfectly plastic law with $\bar{n} \to 0$, then

$$\lim_{n\to 0}\overline{\sigma_r} = \sigma_{c0} \quad (2)$$

where σ_{c0} is the limit flow stress of the composite.

Duva's differential self-consistent model [26] for the reference stress of the composite with rigid spherical particles perfectly bonded in a pure power law matrix gives

$$\overline{\sigma_r} = \sigma_0(1 - V_p)^{-m} \quad (3)$$

where $m \cong 0.39(1-n)+2.5n$, V_p the volume fraction of reinforcement, and σ_0 is the tensile flow stress of matrix.

The stress–strain relationship for the matrix material considered in the paper is rate independent and specified by quasi-state behavior. Based on Mori–Tanaka's average field model (1973) [20], the bulk modulus of the matrix is determined by the following relationship:

$$K_c = K_m + \frac{(K_p - K_m)V_p}{1 + (1 - V_p)[(K_p - K_m)/(K_m + (4/3)G_m)]} \quad (4)$$

where G_m is the shear modulus, which gives

$$G_m = \frac{3(1 - 2\nu_m)}{2(1 + \nu_m)}K_m \quad (5)$$

where υ_m is the Poisson's ratio of the matrix, and K_c, K_m, K_p stand for the bulk modulus of the composite, matrix and particle, respectively, which are formulated as

$$K_i = \frac{E_i}{3(1 - 2\nu_i)} \quad (6)$$

where E_i and v_i ($i = c, m, p$) stand for the elastic modulus and Poisson's ratio of the composite and its components (matrix and inclusion).

The uniaxial work hardening behavior of the matrix is also described by the power law equation:

$$\varepsilon_p = k\left(\frac{\sigma}{\sigma_0}\right)^{N_0} \quad (7)$$

where σ is the uniaxial stress of the matrix, ε_p the plastic strain of the matrix, k the material constant, and $n_0 = 1/N_0$ is the strain-hardening exponent of the matrix. Following the Duva's model [26,28], a composite with hard inclusions will harden with the same strain-hardening exponent as the matrix when the strains are in the fully developed plastic regime. While in real materials, the addition of inclusions will affect the deformation behavior of the monolithic matrix. Therefore, in the present model, the relationship between the strain-hardening exponent of the matrix and the composite is assumed to be represented by the following equation:

$$\bar{n} = \beta n_0 \quad (8)$$

where $\bar{n}$ stands for the hardening exponent of the composite, and β is a coefficient. Substituting Eq. (8) into Eq. (7) and using Eqs. (1)–(6), the mechanical properties of the matrix can be obtained.

3. Finite element model for laser forming

The finite element simulation was conducted using the ANSYS commercial software. The flow chart of the simulation process is shown in Fig. 1, which includes four models, the self-consistent analytical model, the unit cell model, the temperature field (or thermal analysis) model and the structural field (mechanical analysis) model. The mechanical properties