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Plastic flow in metal matrix composites reinforced with particles. Analyzed by FEM

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ABSTRACT

An analysis was made, using the modified Dow micromechanical model and the Finite Elements Method (FEM), considering the behavior in compression of a graphite particles-aluminum matrix composite. It was studied the influence of the reinforced particle radius and the Mixing Volume Fraction, on the plastic yield initiation in the composite. It was also analyzed the spreading of the plastic zone in dependence with the compressive displacement in the microcell model.

INTRODUCTION

In the last years, the interest in developing Metal Matrix Composites (MMCs) has grown up, their mechanical performances making possible to keep the metallic materials competitive against the reinforced plastics, having in view properties like specific strength, fatigue resistance, rigidity etc.

Among the metallic composites, graphitic aluminum alloys have been found to be potential engineering materials for a variety of antifriction and antiwear applications. In such applications, the presence of graphite in the base alloy ensures smooth functioning in service under the conditions of boundary lubrication which are encountered sometimes due to the temporary scarcity of the lubricant.

This paper is concerned with the plastic behavior of an aluminum alloy containing a small volume fraction of second-phase soft spherical particles and its effect on stress transfer. This study has been carried out to understand the basic functions of the plastic behavior in discontinuous MMCs, by the use of a finite element analysis, combined with the application of a unit cell model [1].

It was used, at the start-point, an adaptation of a micromechanical model available in the literature [2,3], namely the model proposed by N.F. Dow (1963), for an element of the composite structure. The elementary volume is considered to be cylindrical in shape, and centered by a reinforcement particle, as it is shown in figure 1.

In this article, the authors are analyzing, using that modified Dow micromechanical model and the Finite Elements Analysis (FEA), the behavior in compression of a composite reinforced with graphite particles. It is studied the influence of the reinforcing particle radius, Rs, and the Mixing Volume Fraction, MVF%, on the plastic yield initiation in the composite.

Also is analyzed the spreading of the plastic zone versus the compressive displacement in the microcell model.

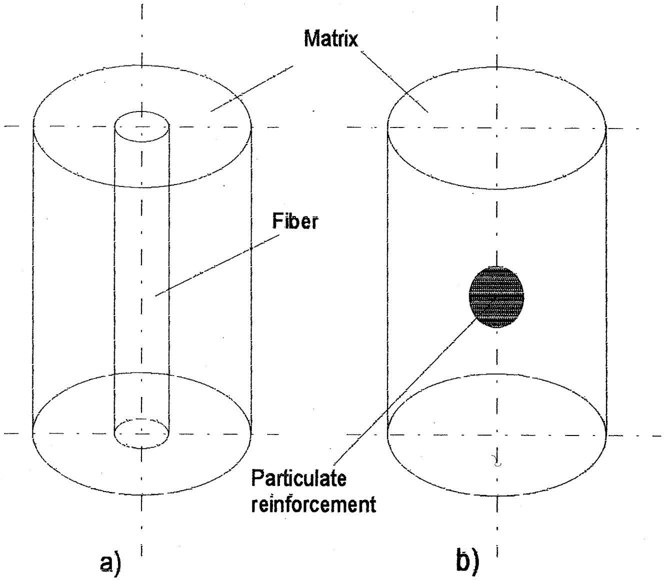

Fig. 1. Micromechanical model: a) original Dow model; b) modified Dow model.

MODELING CONSIDERATIONS

At the aim of the paper one are making two modelings. First, the real part must be modeled with the modified Dow microcell. Then, the characteristics of the FEA model must be established.

At the first stage one must find the dimensions of the microcell as a function of the reinforcing particle radius, Rs, and the Mixing Volume Fraction, MVF%. It is found from experience that the interesting range of variation for the reinforcing particles radius is from 50 μm to 200 μm and - for the MVF% - from 4% to 12%. In these circumstances several analysis with Rs = 50, 100, 150 and 200 μm and MVF% = 4%, 6%, 8%, 10%, 12%. are carried on.

A degree of indeterminacy when establishing the dimensions of the microcell is given by the fact that we don't know the relation between its height, Hc, and diameter, Dc. In order to verify later the results obtained with this model the authors will use cylindrical compression parts, of the Rastegaev type [4], with the diameter of 10 mm and the height of 10 mm. In order to ensure isotropic properties for the modeled material, the authors adopted the same ratio of 1 between the diameter and the height of the microcell. In these circumstances, no matter the dimensions of the modeled part, one can write:

$$Dc = Hc = Rs \cdot \sqrt[3]{\frac{16 \cdot 100}{3 \cdot MVF\%}} \qquad (1)$$

where Dc is the diameter of the microcell;
Hc is the height of the microcell;

Rs is the spherical particle radius [μm];
MVF is the mixing volume fraction [%].

The geometry of the FEA model is established on the base of the Dow model dimensions and taking into account for its symmetry properties. In figure 2 it is presented the free body diagram for the considered model.

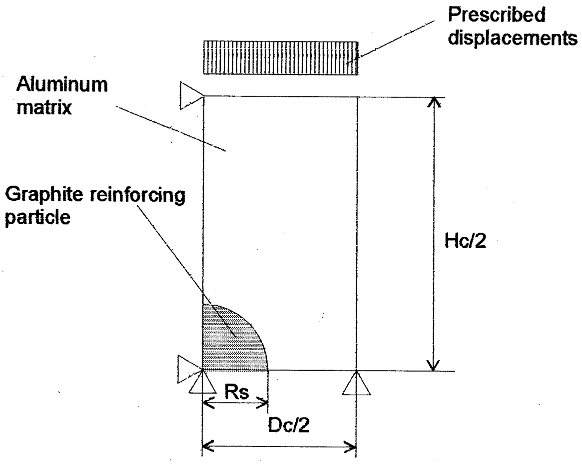

Fig. 2. Free body diagram of the microcell

The symmetry is considered by imposing the appropriate displacement constraints. The loading imposed to the FEA model is of "prescribed displacements" type. A maximum compressive displacement of 1 μm for the upper face of the microcell is considered in all the analysis.

It is established that, in loading, the metal matrix has an elasto-plastic with hardening behavior. The initial yield criterion, that specify the states of stress for which plastic flow first begins is the von Mises equivalent stress. The associated flow rule that connects the plastic strain increment with the stress and stress increment is of elasto-plastic type, with isotropic hardening. In figure 3 is given the stress strain relation for the aluminum matrix of the composite.

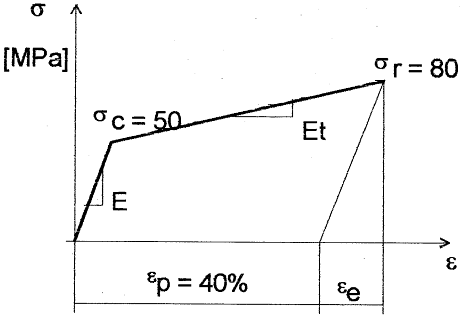

Fig. 3. Stress strain curve for the aluminum matrix

The reinforcing material, namely graphite, is behaving linearly elastic in the whole loading range. The relation between the stresses and strains for this material is given by the Hooke's law. The properties of both materials are synthesized in table I

Table I.

Material	E [MPa]	ν (Poisson)	σ_c [MPa]	Et [MPa]	σ_r [MPa]
Aluminum	0.72E5	0.3	50	0.75E2	-
Graphite	0.05E5	0.3	-	-	6

The nonlinear numerical analysis is done in an incremental manner. The prescribed displacement of 1 μm is divided and applied on the structure in 50 steps. The system of nonlinear equations that results is solved using the modified Newton-Raphson iterative method [4,5].

For each analyzed case it was recorded:

- the compression in the microcell when the plastic flow initiates;
- the compression in the microcell when all the aluminum matrix is in the plastic range.

The analyses are carried on using the nonlinear stress processors produced by ALGOR [6]

RESULTS AND COMMENTS

A number of 20 situations, that corresponds to the Rs and MVF% considered above, are analyzed. The results are showing that the plastic yield surface has the same evolution in the microcell no matter the case which was analyzed. In figure 4 it is presented the evolution with the compressive displacement of the upper face of the microcell of the plastic flow surface in the case of Rs = 100 μm and MVF% = 10%. Qualitatively, this evolution if followed in all of the cases that were analyzed.

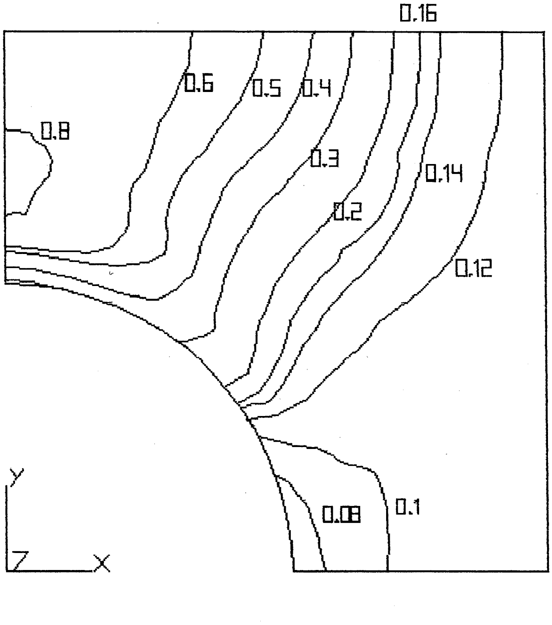

Fig. 4 The plastic flow in the model with Rs = 100 μm and MVF% =10%

In the presented case the microplastic yield initiates at a compression of 0.08 μm in the transverse diametrical plane of the reinforcing particle. It can be observed that in the first stages of compression the plastic surface has a very fast evolution. At a compression of the microcell in the range of 0.12-0.14 μm, the plastic volume is occupying almost 1/2 of the microcell matrix volume. After this compression level, the evolution of the plastic yield surface is much slower.

This behavior cannot be explained by means of the material strain hardening because of the extremely low value of the tangential elasticity modulus Et. Two hypothesis that are in course to be verified by the authors can be taken into consideration:

- The deformation work is directed to that part of the microcell that is opposing the less resistance in deformation. This is the zone that is already in the plastic range.
- The cone of the material that is situated immediately over the spherical particle is laying in a triaxial compressive state of stresses. This state of stresses is unfavorable for the plastic flow.

In the figures 5 and 6 it is presented with the help of some spatial diagrams the global evolution of the plastic zone in all situations that were analyzed.

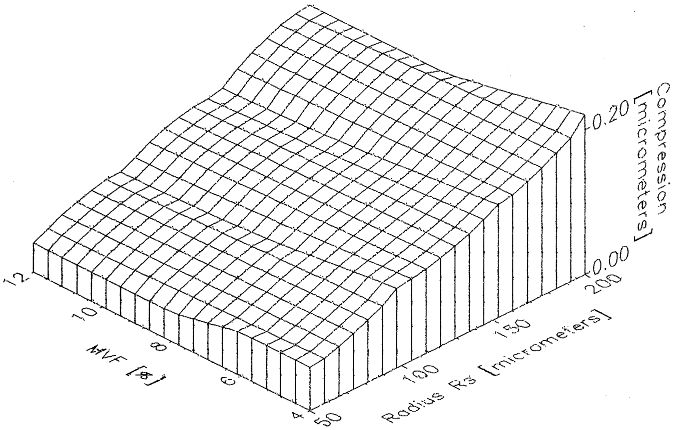

Fig. 5 Compression at which plastic flow occurs.

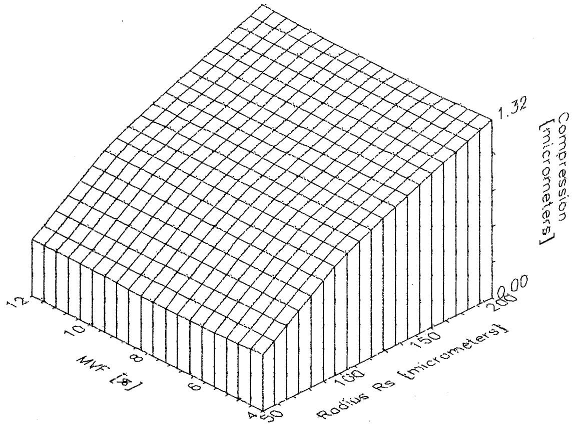

Fig.6 Compression at which the matrix is fully plastic.

The surface in figure 5 is representing the compression of the microcell, in micrometers, in the moment that the plastic flow initiates. The surface in figure 6 is representing the microcell compression, corresponding to the point (Rs, MVF%), in the moment when all the matrix material is in the plastic range. From both figures one can observe that the biggest influence in the plastic flow is assured by the spherical reinforcing radius, Rs. The microplastic yielding appear at a low level of compression for particles with small radius. Thus, in the case of a spherical particle with radius Rs = 50 μm it is found to be sufficient to compress with only 0.04-0.06 μm (according with MVF%) in order to initiate the plastic flow. On the other hand, the plastic flow initiation for the particles with the radius Rs = 200 μm is appearing when the compression is about 0.18 - 0.22 μm. Roughly one can say that the microplastic initiation varies linearly with the radius of the reinforcing particle.

Approximately the same slope in the variation of the compressive loading with the reinforcing particle radius can be found in fig. 6. This fact is coming to strengthen the affirmation stated above that the plastic surface evolution (after it has initiate) is the same no matter the values of Rs and MVF%. For the same radius of the reinforcing particle the influence of MVF% is inconclusive. As it can be seen in both figures 5 and 6, the slopes of the compression surfaces are almost zero in the MVF% direction.

CONCLUSIONS

It can be saying that, when using the micromechanical Dow model to represent a particle-reinforced composite, the plastic surface initiation and spreading is a linear function of only the radius of the spherical particles. As it was shown, the influence of the MVF% on the plastic flow can be neglected. However, there are many others micromechanical models found in the literature that must be tested in the same conditions as in this paper in order to strength this affirmation. Also, the authors are developing an experimental testing program in order to validate the above cited results.

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