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Experimental and numerical study of alumina reinforced aluminum matrix composites: Processing, microstructural aspects and properties

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ABSTRACT

Co-continuous alumina–aluminum composite materials with excellent physical and mechanical properties offer great potentials for lightweight, wear resistant, and high-temperature applications. They combine metallic properties of matrix alloys (ductility and toughness) with ceramic properties of reinforcements (high strength and high modulus), leading to greater strength in shear and compression and higher service-temperature capabilities. Composite materials prepared from a liquid-phase displacement reaction present a unique microstructure in which each phase is a continuous network penetrated by the network of the other constituent. In this study, aluminum–alumina matrix composites reinforced with glass bubbles with low thermal and electrical conductivities are presented. Different characterization techniques were used to determine physical–mechanical properties. Porosity and density measurements were carried out by means of helium gas pycnometer and basic materials parameters were compared such as effect of the sintering process, thermal conductivity, and percentage of the wax. Drop weigh tests, semi static compression tests and also scratch tests were applied to measure the general mechanical and damage behavior of these composites. Microstructural and fracture behavior were evaluated by Scanning Electron Microscopy (SEM).

A three dimensional non-linear finite element model was developed for modeling the impact and compression behavior of alumina reinforced aluminum matrix composite materials. For this stage, ABAQUS/Explicit commercial program was used. The finite element results have shown a good correlation with the experimental data in terms of contact-force and energy histories and also deflection phenomena of the alumina reinforced aluminum matrix composites during the impact was observed between the experimental data.

1. Introduction

Metal matrix composites (MMCs) are advanced materials; for their production, widely used sintering method is one of the main manufacturing processes to obtain composite products applied for high strength, lightweight materials and mainly as high temperature and wear resistance in aerospace and automotive industries [1–4].

Recently, the demands for lightweight materials having a high strength and a high toughness have concerned a lot of care to the development of light and also low cost composite structures and/or composite reinforced with light materials as so called nonconventional materials such as metal and ceramic oxides, glass spheres and/or bubbles, etc. [1–3,5–11]. The Powder Metallurgy (PM) route is known as most commonly used process for the preparation of discontinuous reinforced MMCs. This method is generally used as low – medium cost to produce small parts (especially round and simple shape), tough, the high strength and resistant materials. Since no melting is involved, there is no reaction zone developed, showing high strength properties. For this reason, in the present work, a simple idea was developed on the production of low cost composites by using a simple method (i.e. mixture of aluminum matrix with alumina (Al_2O_3) admixing small size glass bubbles and

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also paraffin-wax and cold pressing + sintering). In reality, Al-alloy based composites have been thought to be in a check out point in the last 20 years as the possibilities of additional improvement of properties of Al alloys by using special heat treatment and microstructural modification had touched its limit. Consequently, new and striking processes of composites have been replacing the conventional techniques, with advantages as far as cost and simplicity of manufacturing are concerned [7–15]. At the first step of this research, a typical composite structure has been created by using paraffin-wax and glass bubble particulates; open spaces created by the volatilization of the paraffin-wax particulates constitute a net of channel porosity which can be partially filled by the aluminum during the semi-solid sintering at the final stage of the process; product is called a low cost light composite [5–7,13–23].

The scope of this work is to identify and investigate the procedures required for a low cost processing route of MMCs containing glass bubbles reinforcements for engineering applications. The current research uses a simple sintering technique under inert environment (mainly argon gas), which has the certain advantages over liquid state methods. Lower processing temperatures decreases the probability of the matrix reacting unfavorably with the reinforcement, improves glass bubbles and other minor particle distribution and presents potentially lower energy consumption, simplified operation procedures with a low time scale, etc. The work carried out during this present research project has the following overall aims: to develop the understanding of powder metallurgy techniques associated with semi-solid sintering in producing aluminum metal matrix composites; to make the persistence of the lowering of costs in the processing of these composites.

2. Experimental conditions

2.1. Materials and green compact

Three different compositions were prepared for the present work: powder of pure aluminum (AA1050 with a density of 2.71 g/cm^3) matrix, Al_2O_3 powders (APC-3017, 3.95 g/cm^3), glass bubbles (5 & 10% wt) and paraffin-wax (5 & 20% wt) were homogeneously mixed. Glass Bubbles, GB, are hollow glass microspheres produced by the company-3M with a density of 0.227 g/cm^3 and with a diameter of 2–20 μm, specified as S38HSS & K1. Waxes (density 0.9 g/cm^3) are very small microspheres (<1–5 μm) binders produced by Clary Chemistry specified as LICOWAX-PE520. All of three compositions contain 2% wt copper. Grain size distribution of the aluminum (~10 μm), alumina (2–15 μm) and copper (<2 μm) were obtained with Laser granulometer. Finally, for sake of simplicity, these three compositions were classified under the name of the following codes:

$$\mathrm{I} - \mathrm{Al(matrix)} + 60\%\mathrm{Al_2O_3} + 2\%\mathrm{Copper} + 5\%\mathrm{Glass\ Bubble} + 5\%\mathrm{Wax} \quad (5\mathrm{GB} - 5\mathrm{W})$$

$$\mathrm{II} - \mathrm{Al(matrix)} + 60\%\mathrm{Al_2O_3} + 2\%\mathrm{Copper} + 5\%\mathrm{Glass\ Bubble} + 20\%\mathrm{Wax} \quad (5\mathrm{GB} - 20\mathrm{W})$$

$$\mathrm{III} - \mathrm{Al(matrix)} + 60\%\mathrm{Al_2O_3} + 2\%\mathrm{Copper} + 10\%\mathrm{Glass\ Bubble} + 5\%\mathrm{Wax} \quad (10\mathrm{GB} - 5\mathrm{W})$$

The powders used in this work, the matrix and additional elements, were analyzed in a differential thermal analyzer to determine the critical temperature-transformation points (solid–liquid zone) and mass loss versus temperature; they had also their size and geometry analyzed by SEM. All compositions were mixed during 1 h in a stainless steel mixer with addition of 2% Zinc Stearate to facilitate the lubrication. The role of the wax used in the matrix is to create nearly homogeneous distribution of empty spaces in the matrix during the sintering process. To prepare green compaction of the powder mixtures, a double action – hydraulic press with a capacity of 100 tons was used. For compaction of the mixture, a stainless steel die with a diameter of 20 mm was used, resulting in green compacts of same size (diameter: 20 mm and height: 30 mm).

2.2. Sintering

Samples of green compacts were sintered under inert atmosphere with argon gas. The treatment for semi-solid state sintering was carried out in two steps: firstly, the volatilization of the wax was made at a temperature of 300 °C for a fixed time of 60 min; at the second step the consolidation of sintering was completed at the temperature of 690 ± 10 °C for a total period of 180 min. Heating rate was 10 °C/min for both steps. During the first step, removing of the wax should be complete by volatilization of the wax to escape, resulting in a partially very small porous structure. These micro-scale porous areas were consolidated during the second sintering step (partial melting of aluminum was achieved at 690 ± 10 °C with a high sintering temperature, very similar to the semi-solid sintering).

2.3. Measurements of the density of the compacted specimens before and after sintering

All of the measurements of the density of the specimens were carried out by pycnometer (digital density meters, work with helium gas) before and after sintering and the results were then compared.

2.4. Mechanical tests and microstructural analyses

Sintered products were submitted to compression tests, carried out in a servo-hydraulic INSTRON Universal test device (model Instron 5500R, equipped with a load cell of 25.000 kgf) with a quasi-static low speed (initial rate: 10 mm/min and second rate: 5 mm/min rate). Maximum load endpoint was 4500N.

Furthermore, dynamic drop tests were carried out on a universal drop weight test device (Dynatup Model 8200 machine) with a total weight of 10.5 kg, punch height of 600 mm and with an impact velocity of ~3 m/s. The wear properties were determined under Scratch tests (detail in the section of 3.3). Microstructures of the composites processed here were observed by using Optical (OM) and Scanning Electron Microscopy (JOEL-SEM). Etching was not made for the examination because there is a remarkable contrast between the aluminum matrix (bright) and the Al_2O_3 (dark appearance).

3. Numerical modeling

At this stage of the present work, internal structure forming the constituents of developed metal matrix composite and modeling of general structural combination were performed by the finite element method. This modeling has been carried out by means of ABAQUS®/explicit software. Specially a subroutines user was developed with FORTRAN® software and embedded in ABAQUS. Modeling is based on the variation of the volume ratio of the reinforcements independently such as Alumina (Al_2O_3), Glass Bubbles (GB) and Paraffin-Wax (PW) used in this work. After that, these particles are randomly distributed in Aluminum (Al) matrix.