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Synthesis and properties of metal matrix composite foams based on austenitic stainless steels –titanium carbonitrides

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ABSTRACT

Metal matrix composite foams based on 316L stainless steel and reinforced with TiC0.7N0.3 were produced by the replication method using polyurethane sponge as a template. The rheological properties of the slurry appeared to be the key issue in the preparation of the composite foams. A homogeneous distribution of TiC0.7N0.3 particles throughout the 316L matrix and a good interaction between the 316L matrix and TiC0.7N0.3 reinforcement particles were obtained. Compression strength results showed that TiC0.7N0.3 particles acted as the real reinforcement medium. The values of the compressive yield strength and the elastic modulus of the metal matrix composite foams increased significantly with increasing TiC0.7N0.3 content when compared to the open cell 316L stainless steel foams.

1. Introduction

Metal foams are an important class of materials that exhibit different attractive characteristics when compared to their solid material counterparts. Cellular (open cell) metallic materials are one of the types of metal foams which are materials with a high volume fraction of voids made up of an interconnected network of struts and plates. The increasing interest in open celled metal foams stems from their ultra-light highly porous (up to porosity of 98%) structure and their properties caused by this structure. Open celled metal foams typically show low density, high surface to volume ratio, low stiffness and permeability to fluid flow. Because of their unique properties they represent alternative materials to several industrial components, i.e. core of sandwich panels, vibration damping components, filters, substrates for catalytic reactions, electrodes, fire screens, porous media for biomedical applications, heat exchanging elements, high stiffness elements for structural applications, etc. However, despite this they are still little known by a wide range of potential consumers [1,2]. If cellular metal structures shall be exposed to demanding corrosive or high temperature environments, stainless steel rather than light metals must be employed. Also steel foams exhibit excellent stiffness to weight ratios when loaded in flexure. In particular, steel foam panels have higher bending stiffness than solid steel sheets of the same weight. Thus there is an increasing interest in steel based metallic foam materials [3–8].

At present, metal foams with higher melting points are usually produced by sintering the metal powders with volatile cellulating agents. Grids or fibbers enable porosity from 40% to 85%. The main shortcoming of these methods is that they do not provide a high uniformity of spatial elements of pore structure and matrix skeleton. At the same time, cells existing in these metal foams prepared by the above mentioned methods are relatively small and sometimes the partial cells are closed. In addition, it is difficult to prepare higher melting point metal foams with three dimensional open – cell network structure by the above methods. The replication of polymeric foam is very convenient for the preparation of three dimensional open cellular foam materials due to its simple process and easiness for scaling up. The transfer of polymeric foam structures to open cell metal foams with up to 98% porosity has been successfully carried out since decades. The replication process involves first the preparation of metal powder slurry by mixing the metal powders with appropriate organic materials. Then the polymer sponge is coated with metal powder slurry, usually performed by immersion or by spraying. Excess slurry is removed by squeezing the sponge, often passing it through rollers. Without this, the cells could become partially closed due to the formation of films bridging the cell struts. After coating and drying, the polymeric sponge and the organic materials are removed by pyrolysis. During this process, a metal frame structure having the same polymeric sponge's open cell structure is obtained. After a final sintering process, open cell metallic foams are produced [1,7].

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Metal matrix ceramic composites have been investigated intensively in the last decades in order to combine the positive properties of the metallic and ceramic components. The resulting composite materials are characterised by an excellent mechanical strength, stiffness and wear resistance combined with a sufficient ductility [9]. The aim of the present study is the development of an innovative composite foam based on 316L stainless steel as a matrix material and $TiC_{0.7}N_{0.3}$ as reinforcing ceramic phase. Titanium carbonitrides are widely used as the reinforcing hard phase in sintered metal ceramic composites. An excellent and unique combination of physical properties such as hardness, high melting point, wear and chemical resistance make these materials attractive in high temperature applications [10]. For the successful application of foams a detailed understanding of their microstructures and mechanical properties is essential.

In this study, open cell metal matrix composite foams were produced with the replication and powder metallurgy method by using 316L stainless steel powders with two different percentages of $TiC_{0.7}N_{0.3}$ (2 and 4 wt%). The rheological behaviour of slurry appeared to be the most important parameter in the preparation of the composite foams. Therefore, the effects of powder concentration and pH value on the rheological properties of the powder slurry were investigated systematically. Mechanical properties of the produced metal matrix composite foams were analysed with compression experiments. Also, microstructure properties of the produced foam materials were studied with optic and scanning electron microscope (SEM).

2. Experimental

In this study, the gas atomized 316L austenitic stainless steel powder with an average particle size of 25 μm was used as the matrix materials. Irregularly shaped $TiC_{0.7}N_{0.3}$ powder with a medium particle size of 1 μm was used as the reinforcing materials. Two different carbide percentages were chosen: 2 and 4 wt%. In order to achieve open cell metallic foams, polyurethane (PU) sponge specimen, in the shape of a rectangular parallelepiped, measuring 50 mm × 50 mm × 20 mm. and having a porosity of approximately 20 ppi (pores per inch) was used as a starting material. To saturate the surface of the PU sponge with metal powders, a solution with different molecular weight polyethylene glycol (PEG) and carboxyl methyl cellulose (CMC) was used as a binder system. The production scheme of the open cell metal matrix composite foams based on 316L stainless steel and reinforced with TiCN was shown in Fig. 1. The specimen preparation stages consisted of mixing, slurry preparation, slurry infiltration, removal of PU sponge and organic binders by thermal pyrolysis and sintering. The base material and $TiC_{0.7}N_{0.3}$ were first dry mixed in low energy blender at 80 rpm for 30 min. by using 6 mm diameter stainless steel balls with a material/ball ratio of 1/5. The slurry preparation for impregnating PU sponge was then started by addition of the powder mixture to deionized water containing carboxyl methyl cellulose and PEGs with different molecular weights (PEG_{600}, PEG_{1000} and PEG_{1500}). The slurry was finally mixed at least 6 h at room temperature. The powder loading content of the slurry was determined by viscosity measurements at 23 °C on a viscometer (Brookfield DV1 Viscometer). The rheological behaviour of the slurries was also characterised by using a stress controlled rheometer Brookfield RST Rheometer,) with a parallel plate (25 mm diameter), under steady shear at 23 °C. Metal powder slurries were prepared in a broad range of pH conditions. In order to determine the influence of the pH, viscosity and sediment speed measurements were carried out by using ammonia at different concentrations in the slurries. The final metal powder slurry was then prepared with regards to all optimum process parameters. The PU sponges were immersed in the slurry to be coated with metal powder. During the coating process, the slurry was frequently subjected to ultrasonic agitation to avoid agglomeration. PU sponges were compressed to fill the void space and then passed through a set of rotating rollers to remove the excess slurry. Subsequently, the samples were placed on a non-stick plastic film surface and then allowed to dry at room temperature for one day. After the pyrolysis behaviour of binders and PU sponge were characterised by thermo-gravimetric measurements (Netzsch STA 409), the dried samples were heated at a ramp rate of 1 °C/min in an Ar–H_2 atmosphere up to 650 °C to burnt out sponges and binders completely. Subsequently, the samples were heated at a rate of 5 °C/min in H_2 atmosphere to the sintering temperature of 1350 °C. The metal matrix composite foams with open porous cellular structure were obtained by sintering the samples at 1350 °C for three hours.

The mechanical properties of the metal matrix composite foams were determined by compression experiments. Compression test was performed on the samples at a crosshead speed of 0.025 mm min^{-1} by using a Shimadzu AGS-X universal testing machine fitted with compression plates. Each foam sample was initially loaded beyond the compressive yield point and cycled through several unload/reload stages at 5.0%, 7.5% and 12% strain. The elastic modulus measurements were made using the

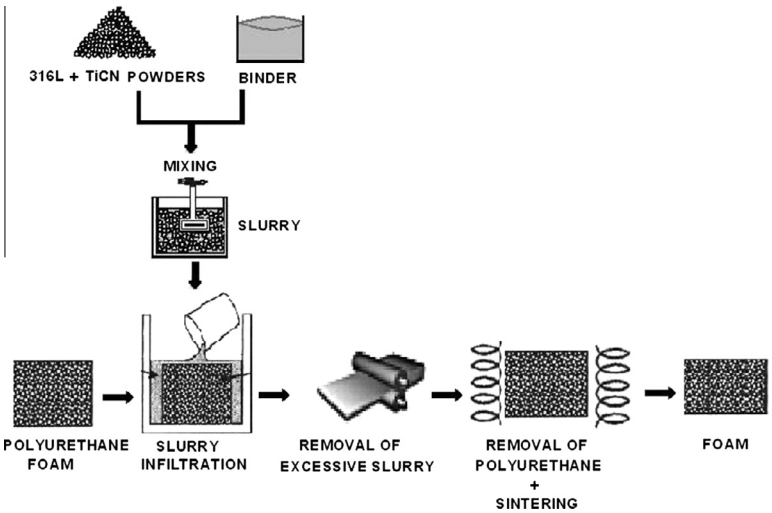

Fig. 1. Production scheme of the metal matrix composite foams based on 316L stainless steel and reinforced with TiCN particles.