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Fatigue in aluminum–steel and steel–steel composite foams

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ABSTRACT

The compression–compression fatigue behavior of two classes of composite metal foams (CMF) manufactured using different processing techniques, was investigated experimentally. Aluminum–steel composite foam processed using gravity casting technique comprises of steel hollow spheres and a solid aluminum alloy matrix. Steel–steel composite foam, processed using powder metallurgy (PM) technique consists of steel hollow spheres packed in a steel matrix. Under compression fatigue loading, the composite foam samples showed a high cyclic stability at maximum stress levels as high as 90 MPa. The deformation of the composite foam samples was divided into three stages – linear increase in strain with fatigue cycles (stage I), minimal strain accumulation in large number of cycles (stage II) and rapid strain accumulation within few cycles culminating in complete failure (stage III). Composite foams under cyclic loading undergo a uniform distribution of deformation, unlike the regular metal foams, which deform by forming collapse bands at weaker sections. As a result, the features controlling the fatigue life of the composite metal foams have been considered as sphere wall thickness and diameter, sphere and matrix materials, processing techniques and the bonding strength between the spheres and matrix.

1. Introduction

Metal foams are cellular structures characterized by their high porosity levels and an interesting combination of properties such as low density, high specific strength and good energy absorption under compressive loading [1,2]. The behavior of metal foams under monotonic compression loading is widely reported in literature [3–9], and to a lesser extent their fatigue behavior under compression loading [10–16]. The successful implementation of metal foams in structural applications (beams and panels in boat hulls, structural components of vehicles, cladding of buildings, helicopter landing gear and car body parts), where the loading is cyclic in nature, is dependent on an understanding of their fatigue behavior [17–19]. Under cyclic loading, metal foams are known to undergo progressive crushing achieving large strains prior to densification [10]. Unfortunately, metal foams also suffer from limitations owing to their non-uniform and irregular cellular structure [20,21]. The hollow sphere foams processed from pre-formed metallic hollow spheres of uniform size and shape showed some improvement in mechanical properties [22] over other metal foams. But the improvement in the mechanical properties is not significant enough, as the strength of the hollow sphere foam depends on the weak point/line contacts established between individual spheres. Composite metal foams (CMF) manufactured using either powder metallurgy (PM) or casting have a matrix that holds the hollow spheres together. Due to the presence of the metallic matrix, the composite foams have better mechanical properties under compression than other metal foams, making them a better alternative for energy absorbing applications [23–25]. Since an increasing number of applications are being explored for composite metal foams, which may include monotonic and cyclic loads, a fundamental understanding of their fatigue behavior is necessary. In the present study, we catalogue the results of compression–compression fatigue loading on composite metal foams, their deformation behavior, failure mechanisms and correlation between their mechanical properties and microstructure.

2. Materials and experimental procedure

The composite metal foams were processed using two methodologies – powder metallurgy and gravity casting. The main difference in the two processing techniques is the ability to use similar and dissimilar materials for the matrix and hollow spheres to produce the composite metal foams. The hollow spheres used in the processing of composite metal foams were made of low carbon steel (LC) and 316L stainless steel (SS). The spheres were produced using a powder metallurgy process at Fraunhofer Institute, Germany [26]. The LC–PM foam consists of LC steel spheres and LC steel powder while the SS–PM foam is made of SS spheres and SS powder. The PM samples were processed using various sphere sizes. LC–PM foams were produced in two batches: one batch with spheres of 3.7 mm OD (outside diameter) and 0.2 mm wall thick-

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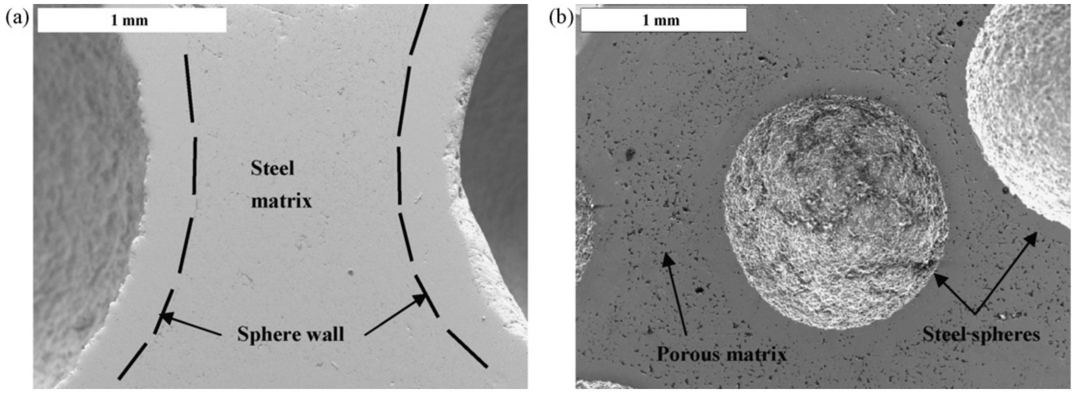

Fig. 1. SEM images of PM composite foams showing the presence of porosities in the matrix as well as the integrated interface between spheres and matrix in (a) 3.7 mm low carbon steel composite foam sample and (b) 2.0 mm stainless steel composite foam sample.

ness, second batch with spheres of 1.4 mm OD and 0.05 mm wall thickness. SS–PM foams were made up of spheres with an outside diameter of 2.0 mm and wall thickness of 0.1 mm. Three LC–PM foams and four SS–PM foams were tested for fatigue endurance limits in this study. Further details about processing of PM composite foams are presented elsewhere [23–25,27]. In the casting technique, molten aluminum alloy A356 (Al–7% Si) was used as the metal matrix to infiltrate spaces between the steel hollow spheres. The aluminum–low carbon steel composite foams (Al–LC), consists of Al matrix and LC steel spheres and the aluminum–stainless steel composite foams (Al–SS), consist of Al matrix and SS spheres. The spheres used in the processing of all cast composite foams have an outside diameter of 3.7 mm with a wall thickness of 0.2 mm. Fatigue tests on four Al–LC samples and two Al–SS samples are reported in this study. Further details about the processing and properties of Al–steel composite foams are presented elsewhere [23–25,28,29]. Thin slices of PM and cast foam samples were used to investigate their microstructure using optical and scanning electron microscopy imaging (SEM), while rectangular cuboids of the foam samples were used for mechanical testing. The test samples were machined to the correct size, having at least 8–10 spheres in each direction using a linear precision saw. The test samples were then surfaced using progressive grinding and the SEM samples were polished using a progression of diamond slurries. SEM images were taken using a Hitachi S-3200N variable pressure scanning electron microscope equipped with Oxford Isis energy dispersive X-ray spectroscopy system. The SEM images were used to examine the bonding between spheres and matrix and to identify the various phases formed in the foam's microstructure. The SEM/EDS analysis was used to chemically characterize the various phases and precipitates identified in the microstructure, sphere walls and the matrix. Further characterization of the constituents in the composite foams (spheres, matrix and precipitates) was obtained from microhardness indentation tests carried out using Vicker's microhardness tester. Compression–compression fatigue tests of composite foam samples were performed using MTS 810 universal testing machine under load control at fixed load ranges and amplitude. The fatigue testing was conducted at a frequency of 10 Hz with a fixed R-ratio ($R = \sigma_{min}/\sigma_{max}$) of 0.1. The foam deformation was monitored by continuously tracking and recording crosshead displacements. A Kodak EasyShare DX6490 4.0 megapixel digital camera was used to record the deformation sequence during the fatigue tests. The digital images were studied to identify onset of any unstable damage in the sample and to understand the macro-scale fatigue mechanisms.

3. Microstructural observations

The PM foam microstructure was observed to consist of sphere walls with a larger grain structure, lower percentage of porosity and higher percentage of precipitations and secondary phases than in the matrix. Pearlite precipitations were found to be present in the LC steel sphere walls, while grain boundary precipitations of the form $M_{23}C_6$ rich in Chromium were found in the stainless steel sphere samples. The large grains and higher precipitations in the sphere walls as compared to the matrix are due to the exposure of spheres to high temperature during the sintering process. Observation of SEM images of PM foams, as shown in Fig. 1(a), has shown that the spheres and matrix have bonded well with no interface between

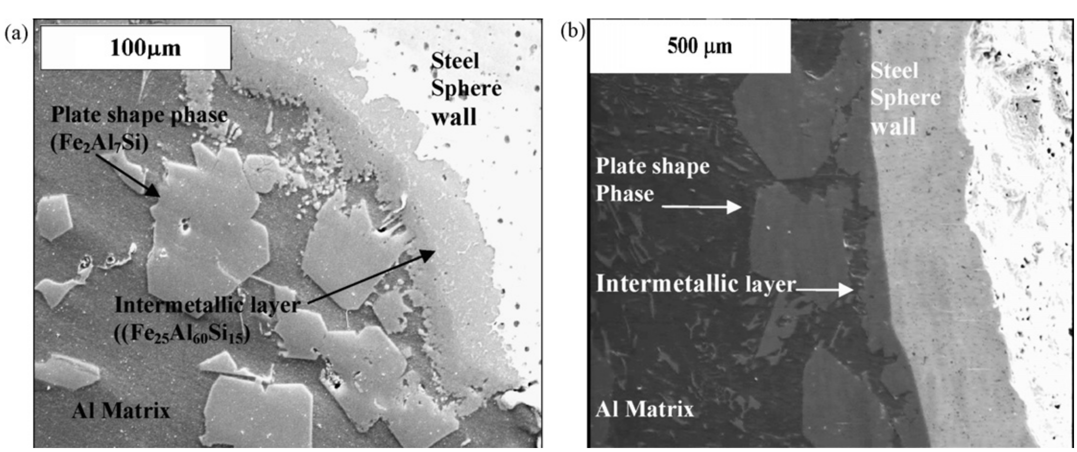

Fig. 2. SEM images of cast composite foams showing the interface layer between the sphere and matrix in (a) Al–low carbon steel composite foam sample and (b) Al–stainless steel composite foam sample.