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Processing, Properties, and Performance of Composite Materials

Manufacture and Mechanical Properties of Metal Matrix Syntactic Foams

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Abstract

Metal matrix syntactic foams are a class of composite materials consisting of a continuous metal matrix embedded with hollow or porous ceramic particles. In comparison with metal foams, they have higher compressive yield strength and more homogeneous mechanical properties, although they usually have higher densities. Because of the existence of porosity, they also have the ability to absorb impact energy. They have the potential to serve as lightweight structures as energy absorbers against impact or as replacement bone implants. The paper introduces Al, Fe and Ti syntactic foams fabricated either by pressure melt infiltration or by powder metallurgy. Their microstructure and compressive behaviour are studied and the characteristics of the two manufacturing methods are compared.

Introduction

Syntactic foam is a composite material that has hollow or porous ceramic particles embedded in a continuous polymer or metal matrix [1]. Metal matrix syntactic foams are a relatively new class of materials [2-9]. In comparison with polymeric syntactic foams, they have higher strength and can be used at much higher temperatures and more harsh environments. In comparison with metal foams, they have higher compressive yield strength, more homogeneous mechanical properties and better energy-absorbing capability due to extensive strain accumulation at relatively high plateau stresses [3], although they usually have higher densities. As a consequence, metal matrix syntactic foams have many potential applications, for example, as packing materials, safety devices and automobile bumpers against impact and crash.

Among the recent work on metal matrix syntactic foams, the majority is based on systems of Al or Mg matrices [2,3-5,7]. This is because Al and Mg not only have low densities but also can be easily manufactured by casting due to their low melting points. Research on other metal systems has rarely been reported in the literature, largely because of the difficulty involved in processing metals with higher melting points. There is a need to develop syntactic foams with other metal matrices for a widened scope of applications of this class of materials.

This paper describes our work on the manufacture of metal matrix syntactic foams with three different matrices. Based on the previous work [9-11], the microstructure and properties of Al matrix syntactic foams manufactured by the melt infiltration method are further studied. A powder metallurgy method is developed for manufacturing Fe and Ti matrix syntactic foams. The characteristics of the microstructure and mechanical properties of these syntactic foams are investigated and the two different manufacturing methods are compared and discussed.

Al Matrix Syntactic Foam

The raw materials used for fabricating the Al matrix syntactic foam samples were 6082 Al alloy and a ceramic microsphere (CM) powder, E-spheres, supplied by Pty Ltd Australia. The CM powder has a composition of ~60% SiO_2, ~40% Al_2O_3 and 0.4-0.5 % Fe_2O_3 by weight, and has an effective density of 0.6 g/cm^3, which is the mass of the powder divided by the volume the particles occupy without the air void between them. The as-received CM powder was divided into four size groups with the diameter ranges of 20-75μm, 75-125μm, 125-250μm and 250-500μm, which are designated as CMs I, II, III and IV, respectively. The particles of the CM powder are either porous or hollow. The hollow CMs are nearly perfect spheres with a solid shell and a smooth surface, while the porous CMs are nodular with a rougher surface. Both types have a very similar porosity of about 80%. The particles in CMs I and II are mainly hollow; those in CM III are one third hollow and two thirds porous; those in CM IV are mainly porous. Fig. 1(a) and (b) show the optical micrographs of CMs I and IV, which typify the morphologies of the hollow and porous particles of the E-spheres.

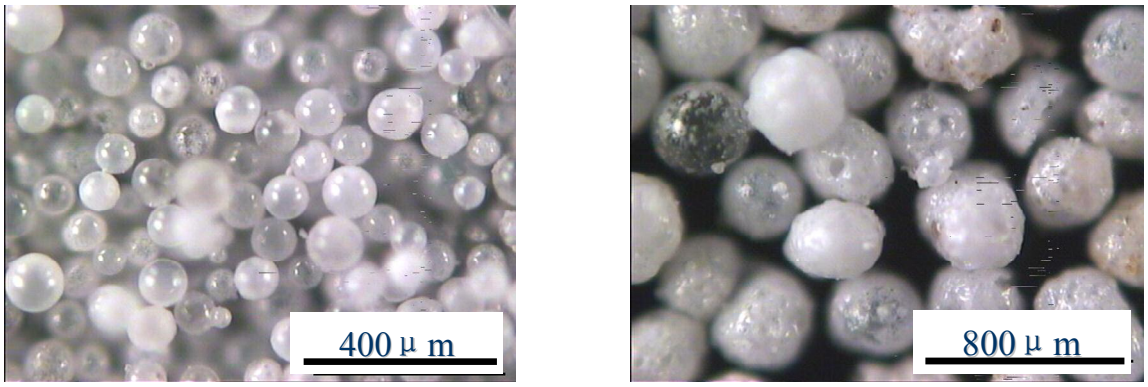

Fig. 1 Typical morphologies of the E-spheres (a) hollow particles and (b) porous particles

The Al matrix syntactic foam samples were manufactured by a melt infiltration process, which is described in [9]. A block of Al 6082 alloy was placed at the top of a predetermined amount of CM powder contained in a steel tube and was heated in an electric furnace at 700ºC for 30min. The assembly was removed from the furnace and the molten Al alloy was pressed into the CM powder. After complete solidification, the syntactic foam sample was removed from the tube and then machined to a cylindrical shape with a diameter of 21mm and a length of 24mm. The sample was homogenized in air at 540°C for 100min and then quenched in water, followed by aging at 180°C for 10h. The syntactic foam samples were designated as Foams A, B, C and D according to the CMs used, corresponding to CMs I, II, III and IV, respectively.

Fig. 2 is the micrograph of the cross section of a typical Al matrix syntactic foam. In all the syntactic foams, the CMs are randomly and homogeneously distributed in the Al 6082 matrix and account for around 60% in volume. The measured densities of the syntactic foam samples varied slightly in a narrow range of 1.4-1.45 g/cm^3. Most CMs in the syntactic foam samples were intact during fabrication. However, a small number of CMs were infiltrated with molten Al, as indicated by arrows in Fig. 2. The infiltrated CMSs are mainly porous ones. In any case, they are less than 10% of all the CMs in the foams.

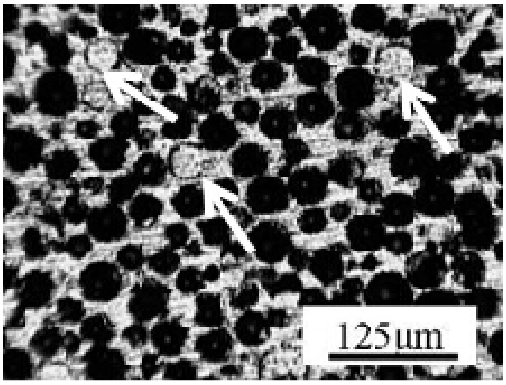

Fig. 2 Optical micrograph showing the cross section of a typical Al matrix syntactic foam

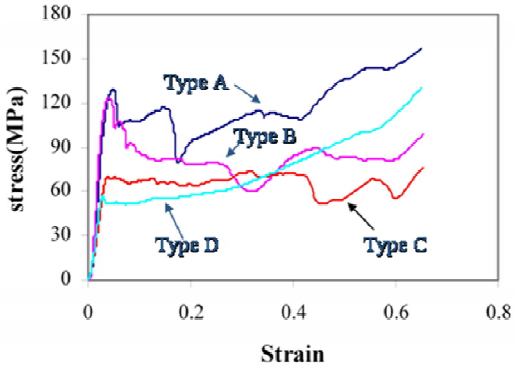

Fig. 3 Compressive stress-strain curves of Al matrix syntactic foams

Fig. 3 shows the representative quasi-static compressive stress-strain curves for Foams A, B, C and D. All four curves have an initial elastic region with a linear stress-strain relationship, followed by plastic deformation. The stress at which large scale plastic deformation starts in the compression of a cellular solid is termed as plastic-collapse strength, as the cell structure starts to collapse at this stress [12]. The plastic-collapse strengths and the corresponding strains for the foams are shown in Table 1. These four foams show different behaviour in the subsequent plastic deformation. Foams A and B have several remarkable stress drops. Foams C and D show a near-plateau region of plastic deformation where the strain increases extensively under a relatively narrow range of stresses. It indicates that syntactic foams with hollow CMs are stronger and more apt to brittle fracture, while those with porous CMs are weaker and experience more steady deformation.

Table 1 Plastic-collapse strength and strain of Al matrix syntactic foams

Foam	A	B	C	D
Plastic-collapse strength (MPa)	130	123	73	57
Plastic-collapse strain	0.045	0.04	0.035	0.038

Fe Matrix Syntactic Foam

The Fe matrix syntactic foam samples were manufactured by powder metallurgy. The raw materials were a water-atomised Fe powder supplied by Pometon and the CM II powder of the E-spheres. The particles of the Fe powder fall within the size range of 100 – 200 μm. The particles are irregular as shown in Fig. 4. The Fe and CM II powders were mixed at a pre-specified volume ratio with a small amount of binder (~5%). The volume percentage of Fe in the sample was 40%, 50%, 60% or 70%. The mixture was compacted into a preform under a pressure of 150 MPa within a steel tube, using a hydraulic press. The steel tube had an internal diameter of 21 mm and a height of 40 mm. The preform was sintered in a furnace at a temperature of 850 °C for four hours and then allowed to cool back to room temperature. It was removed from the tube and then machined into regular shape for subsequent mechanical tests.

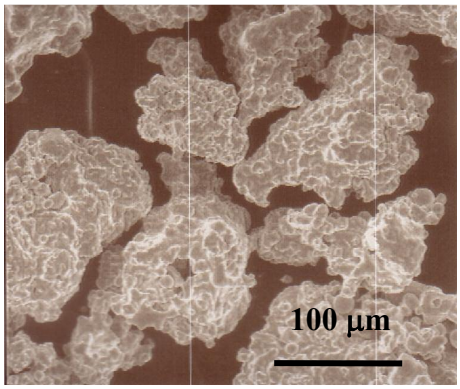

Fig. 4 SEM micrograph showing the morphology of the Fe powder

The as-manufactured Fe matrix syntactic foams with Fe volume percentages of 40%, 50%, 60% and 70% have densities of 3.8, 4.1, 4.4 and 4.6 g/cm^3, respectively. All foams have a uniform structure with the CMs distributed in the Fe matrix homogeneously. However, a considerable number of the CMs are broken as shown in Fig. 5. The damages to the CMs are mainly caused by the compaction process. The compressive strength of the CMs measured in the powder form is in the order of 50 MPa [9]. The CMs can withstand much higher stresses when surrounded by a metal matrix because of less stress concentrations. However, the weaker CMs will collapse under the compaction pressure of 150 MPa. Further investigations on the relationship between compaction pressure and sphere damages are needed. To reduce the number of damaged CMs, lower compaction pressures are necessary.

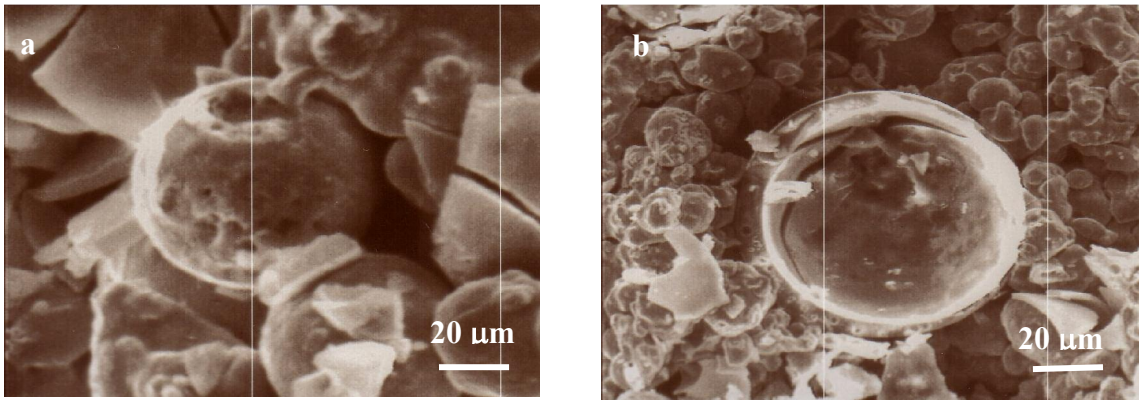

Fig. 5 SEM micrographs showing (a) whole and shattered spheres and (b) a cut-through sphere in the Fe matrix at a fracture surface of a Fe matrix syntactic foam (70% Fe)

Fig. 6 shows the compressive stress-strain curves of the Fe matrix syntactic foams with different volume percentages of Fe. Each curve has an initial elastic region with a linear stress-strain relationship, followed by a plastic deformation region with a much gentler slop. For the foams with a fixed volume percentage, there are significant variations among different samples in compressive strength and corresponding strain. Table 2 shows the average values of collapse

strength, compressive strength (maximum stress) and the strain corresponding to the compressive strength for the foams with different Fe volume percentages. Both low (40%) and high (70%) Fe volume percentages lead to low collapse strengths, while medium (50% and 50%) Fe volume percentages lead to higher collapse strengths. The compressive strength and the corresponding strain, however, increase with increasing Fe volume percentage.

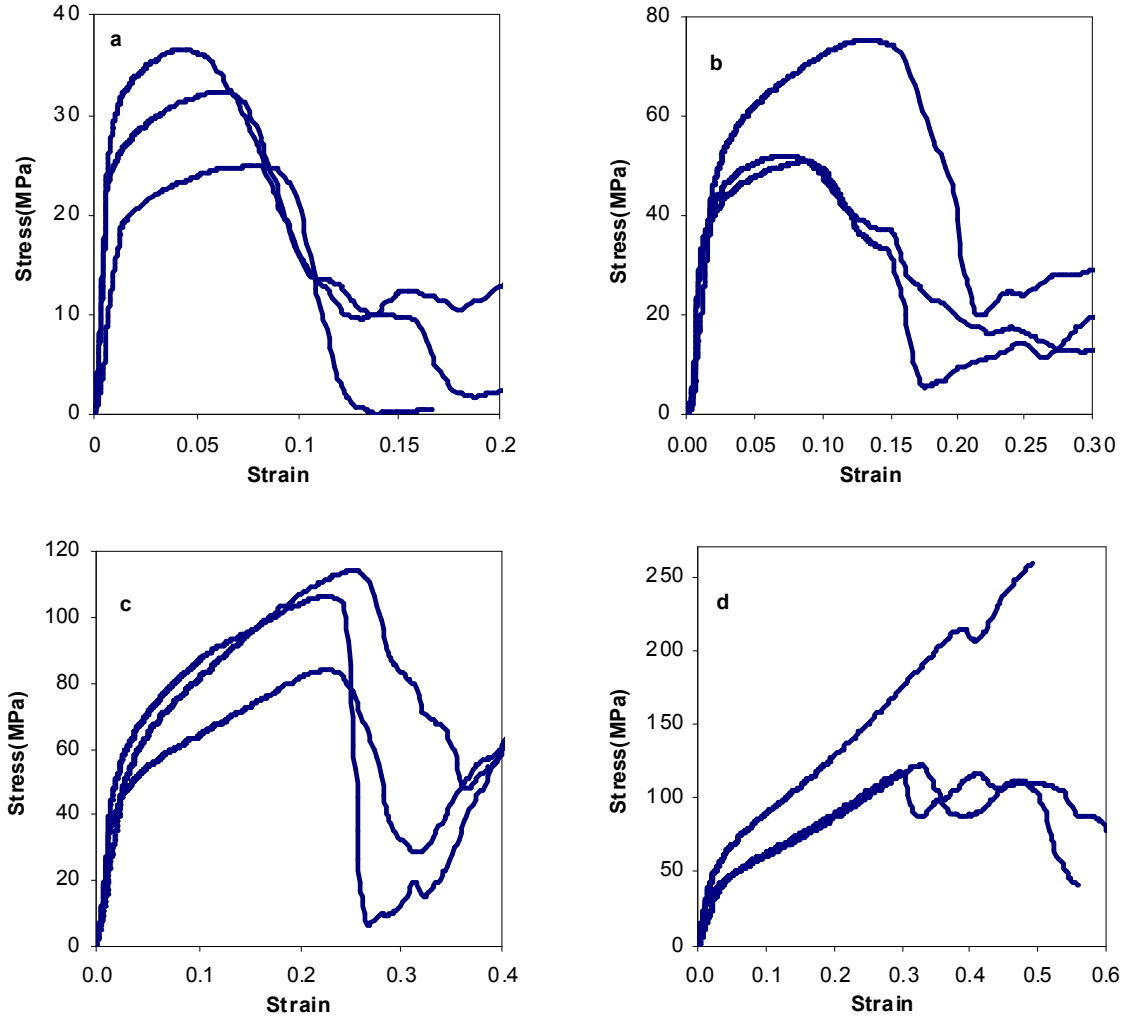

Fig. 6 Compressive stress-strain curves of Fe matrix syntactic foams with different volume percentages of Fe: (a) 40%, (b) 50%, (c) 60% and (d) 70%

Table 2 Average collapse strength, compressive strength and strain of Fe matrix syntactic foams

Volume percentage of Fe (%)	40	50	60	70
Collapse strength (MPa)	25	41	47	36
Compressive strength (MPa)	31	59	101	151
Strain	0.07	0.11	0.24	0.34

Ti Matrix Syntactic Foam

The Ti matrix syntactic foam samples were also manufactured by powder metallurgy. The raw materials were a HDH Ti powder (99.4% Ti, 0.37% O, 0.04% Fe and 0.04% Cl) supplied by Active Metals Ltd and the CM III powder of the E-spheres. The particles of the Ti powder are angular and have sizes less than 45 μm, as shown in Fig. 7. The Ti and CM III powders were dehydrated at 200ºC. The CM III powder was further heated to 800ºC for 2 hours to remove any contaminants contained in the spheres. The Ti and CM III powders were mixed at a pre-specified volume ratio. The volume percentage of Ti in the sample was 40%, 50% or 60%. The mixture was then compacted into a preform under a pressure of 100 MPa within a steel tube with a diameter of 44 mm, using a hydraulic press. The preform was sintered in an electric furnace at a temperature of 1000°C for one hour and then allowed to cool back to room temperature in argon. It was removed from the tube and then machined into a regular shape for subsequent mechanical tests.

Fig. 8 shows the fracture surface of a typical Ti matrix syntactic foam. All foams have a uniform structure with the CMs distributed in the Ti matrix homogeneously. However, as in the Fe matrix syntactic foams, a considerable number of the CMs are broken under the compaction pressure.

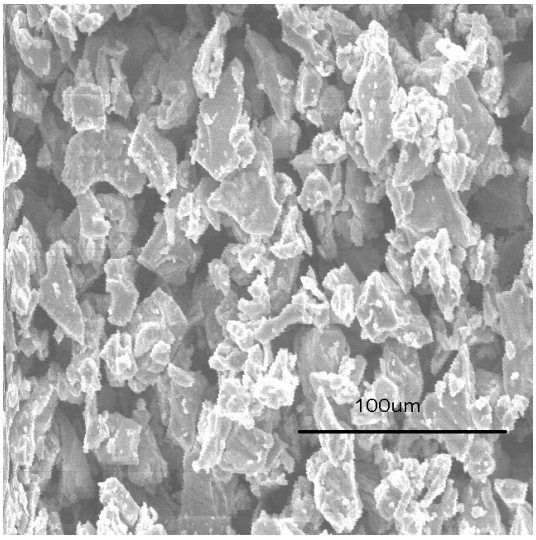

Fig. 7 SEM micrograph showing the morphology of Ti powder

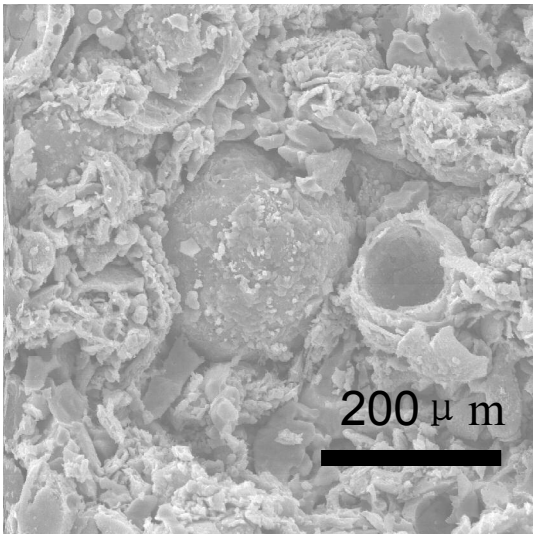

Fig. 8 SEM micrograph of the fracture surface of a Ti syntactic foam sample showing the intact and broken ceramic microspheres

Fig. 9 shows the compressive stress-strain curves of the Ti matrix syntactic foams with different volume percentages of Ti. Each curve has a nearly linear region before a sudden drop in stress occurs. Subsequently, the stress increases and drops for several times. One sample, Fig. 9(a), was subjected to several cycles of loading-unloading in the linear region. The deviations of

the loading and unloading parts from the initial curve are not significant. This indicates that the linear region is nearly elastic. The sudden drops in stress corresponded to fracture and appearance of cracks, and the first drop in stress occurred at small strains for all the foams. This indicates that the as-manufactured Ti matrix syntactic foams are brittle in nature. Table 3 shows the compressive strength (maximum stress before the first major sudden drop) and the corresponding strain for the foams with different Ti volume percentages. The compressive strength and strain do not vary significantly with increasing Ti volume percentage.

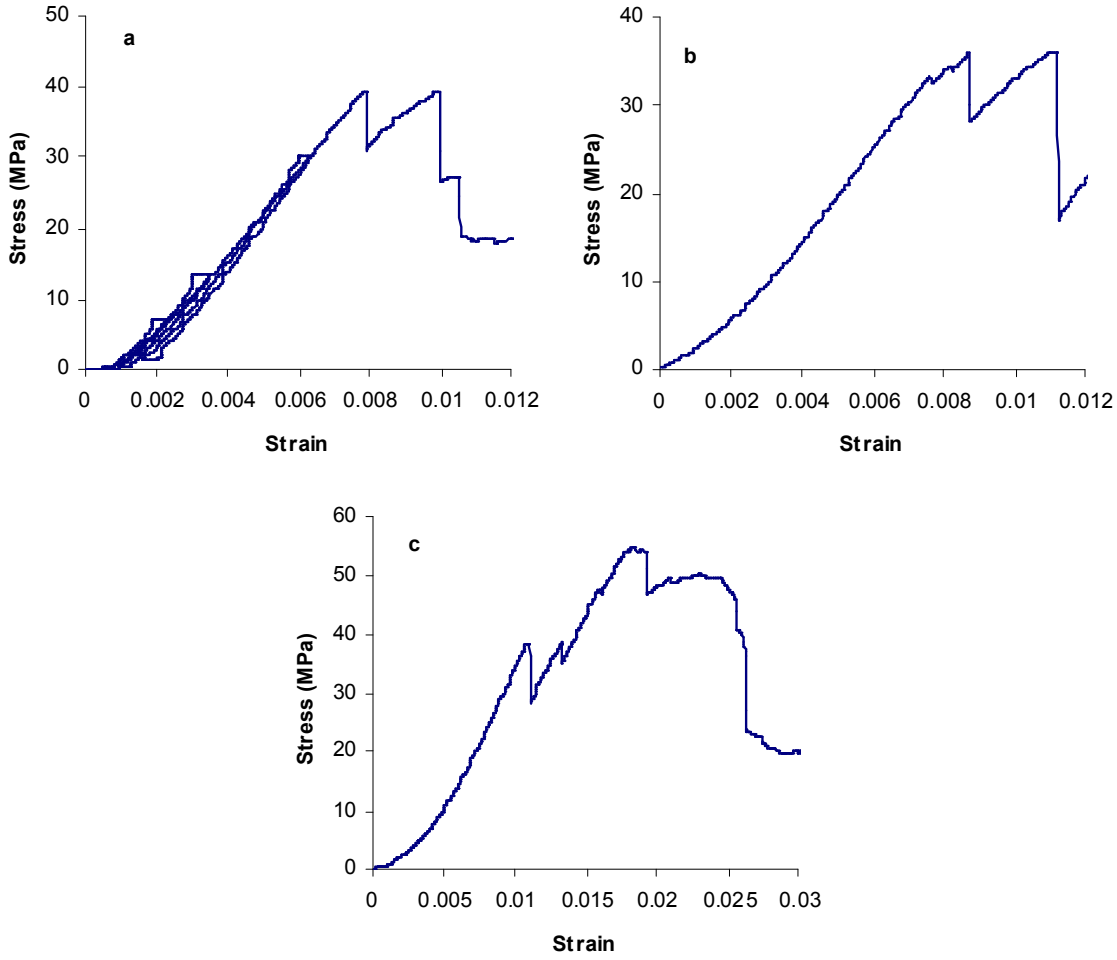

Fig. 9 Compressive stress-strain curves of Ti matrix syntactic foams with different volume percentages of Ti: (a) 40%, (b) 50% and (c) 60%

Table 3 Compressive strength and corresponding strain of Ti matrix syntactic foams

Volume percentage of Ti (%)	40	50	60
Compressive strength (MPa)	39	36	39
Strain	0.008	0.009	0.011

Summary

Al matrix syntactic foams have been manufactured by melt infiltration, and Fe and Ti matrix syntactic foams have been manufactured by powder metallurgy. Melt infiltration is a rapid process suitable for metals with low melting points. It produces a dense matrix with the CMs distributed uniformly in it. The resulting metal matrix syntactic foams have better structural integrity and good compressive properties. However, the volume ratio between the metal matrix and the ceramic spheres cannot be varied. In contrast, powder metallurgy can be applied to metals with higher melting points. The volume ratio between the metal matrix and the ceramic spheres can be varied in a wide range. Therefore, the mechanical properties can be tailored to meet the specific needs of the intended applications. However, solid state sintering is a time consuming process. The matrix of the syntactic foam produced by powder metallurgy often contains considerable amounts of defects, such as voids and oxides. High compaction pressures required for enhancing the subsequent sintering can lead to significant damages to the ceramic spheres. Further work is needed to optimize the powder metallurgy process for manufacturing metal matrix syntactic foams.

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