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Compressive property and energy absorption characteristic of 3D open-cell Ni−Cr−Fe alloy foams under quasi-static conditions

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Abstract: Reticulated open-cell Ni−Cr−Fe foams were manufactured by gas-phase codeposition of Cr and Fe onto the struts of pure Ni foam at 1050 °C, and then the samples were homogenization treated at 1200 °C in a vacuum atmosphere. The quasi-static compressive behavior and energy absorption characteristics of the Ni−Cr−Fe alloy foams with different Cr and Fe contents were discussed. The mechanical properties of these open-cell Ni−Cr−Fe alloy foams were also comparable with the pure Ni foams or the hypothetical Ni−Cr−Fe foam model. The results show that although the alloy foam struts show the similar hardness, the compressive strengths and energy absorption properties of the open-cell Ni−Cr−Fe alloy foams increase with increasing the Cr and Fe contents. The stress—strain behaviours of the Ni−Cr−Fe alloy foams are as smooth as those of nickel foams, indicating that the Ni−Cr−Fe alloy foams are the characteristic of typical ductile metallic foam. The energy absorption capabilities of the Ni−Cr−Fe alloy foams exhibit 22 times higher than that of the pure Ni foams. Simultaneously, the compressive strength of the Ni−Cr−Fe alloy foams at ambient temperature is in agreement with theoretical prediction by Gibson–Ashby model.
Key words: metallic foam; Ni foam; vapour deposition; coating; heat treatment; pack cementation

1 Introduction

Recently, there has been a considerable increasing interest in using open-cell metal foams as catalyst supports, filters, electrodes, heat exchangers, etc, because of their unique combination of high porosity, relatively high stiffness and reaction surface area [1,2]. These applications require a relatively high mechanical performance as well as elevated corrosive and oxidation resistance. However, the mechanical performance of the open-cell metal foams is found to be strongly affected by the foam characteristics like shape and size of the cells, cell wall thickness and cell connectivity. The 3D open-cell nickel-based alloy foams with uniform pore structure are attractive candidates for automotive exhaust gas purification due to their good wear resistance and durability at high temperatures [3]. However, the traditional liquid-phase methods for processing open-cell metal foams present severe challenges due to their high melting point and complicate 3D open-cell network structure [4]. When the solid-state techniques are applied to open-cell alloy foams, the shape, size, spacing and connectivity of the pores are difficult to control and the porosity achieved is much low [5].

At present, the open-cell pure nickel foams are mainly produced by electrolytic deposition method. However, the major limitation of electrolysis deposition process is that only a few metallic elements are deposition (nickel-based alloys are difficult) [6]. In addition, non-uniform deposition may occur due to the irregular shaped geometry. Currently, more interest focuses on the chemical or physical vapour deposition methods using the organic foam as the substrate. However, vapour decomposition of the least expensive chemical precursors occurs at high temperatures where the thermal stability of the polymer template must be taken into consideration [6].

The pack cementation process is an efficient and cost effective method to improve the surface properties

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of materials [7]. Pack-chromizing has been widely applied to steels and superalloys to improve their high temperature oxidation resistances [8,9]. Recently, HODGE and DUNAND [4] demonstrated that open-cell pure Ni foams could be pack-aluminized into homogenous NiAl foams with 28%−33% Al, but the NiAl foams were brittle at ambient temperature due to the very low toughness and ductility of NiAl.

The Ni−Cr−Fe system is an important model alloy for nickel-based alloys because of their good corrosion resistance and high strength at elevated temperatures [10]. The constitution of Ni−Cr−Fe system has been well determined in the region of 0–40% Fe and 20%−46% Cr [11]. Especially Inconel 690 alloy with the high chromium content is a high-performance nickel-based alloy used in corrosive and high-temperature environments [12].

In the present work, the feasibility for synthesis of the Ni−Cr−Fe alloy foams was investigated by co-deposition of Cr and Fe onto open-cell nickel foams. Based on the compositions of Inconel 690 (60% Ni, 30% Cr, 9.5% Fe, 0.03% C), a new kind of Ni−Cr−Fe single-phase austenitic, oxidation-resistant alloy foam is developed by increasing and modifying some of the alloying elements. The quasi-static compressive behaviour and energy absorption characteristic of Ni−Cr−Fe alloy foams with different Cr and Fe contents are discussed. The mechanical properties of Ni−Cr−Fe alloy foams are also comparable with the pure Ni foam and theoretical predictions for Gibson−Ashby model.

2 Experimental

2.1 Initial open-cell nickel foams

The open-cell nickel foams with porosities of 98% (20 pores per linear inch) were fabricated by electro-deposition on a polymer substrate. Then the polymer foam was removed by a suitable heat treatment. The structure of nickel foam was the quasi exact replication of the original polyurethane foam. The element compositions of the nickel foam are listed in Table 1. The SEM images of open-cell nickel foam are shown in Fig. 1, and the nickel foam was an interconnected network of solid struts or plates which formed the edges and faces of cells. The regular round shape of the nickel foam was more uniformly distributed throughout the sample compared with that of the alloy foam by the infiltrating process method [13].

Table 1 Element compositions of open-cell nickel foam (mass fraction, %)

Ni	Si	Cu	S	P	Cr	Al	Zn
98.17	0.2	0.2	0.06	0.2	0.97	0.09	0.11

2.2 Synthesis of open-cell Ni−Cr−Fe foams

The open-cell nickel foam was ultrasonically cleaned. The pack consisted of 5% NH_4Cl, 5% Fe, 20% Cr powder (with an average particle size of 55 μm) and 70% Al_2O_3 filler powder (with an average particle size of 45 μm). A total pack mass of 125 g was poured in a stainless-steel can in which the nickel foam (with mass about 0.56 g) was embedded in the pack powder. The pack co-deposition process was carried out at 1050 °C for 4−10 h, and then the stainless-steel was allowed to cool to room temperature.

The samples were encapsulated in evacuated quartz tubes and annealed at 1200 °C for 12 h and 48 h. The mass gains of the samples were measured by using the BP211D analytical balance. The relative density of alloy foam was defined as the foam density divided by that of the solid material.

The phases and compositions of all alloy foams before and after homogenization were checked by energy dispersive X-ray spectroscopy (EDS). Vickers micro-hardness measurements were made in a Shimadzu micro hardness tester HMV−2000, using a force of 0.98 N and a holding time of 15 s. The quasi-static compressive tests were conducted in an Instron 5569 testing machine with a cross-head speed of 0.01 mm/s. The samples with

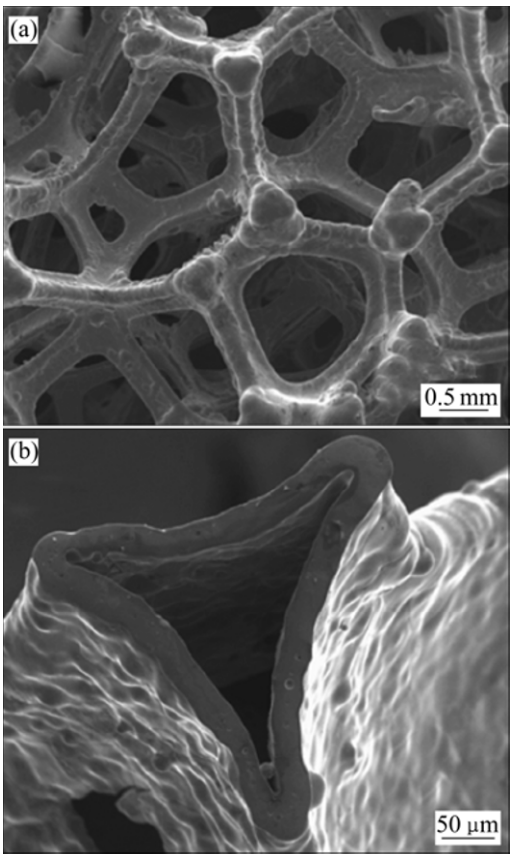

Fig. 1 SEM images of open-cell nickel foam: (a) Overall morphology; (b) Cross-section of foam strut