

## Innovative processing of porous copper composite by chemical reaction

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### Abstract

Metal foams are a new, as yet imperfectly characterized, class of materials with low densities and novel physical, mechanical, thermal, electrical and acoustic properties. This article describes a method named Self-propagating High-temperature Synthesis (SHS) process to produce open cell copper composite foams. Porous Cu composite was fabricated by the reactions between CuO, Al and C powders. The gas released during these reactions and also the initial porosity of the green powder compact were the source of the produced pores. The relative densities of the copper composite foams have been investigated for different ratios of powder weights. Optical microscopy and scanning electron microscopy (SEM) were utilized to characterize the porous samples. Analyzing the properties of the composite foams showed that the optimum weight fraction for blending initial powders was %84 CuO, %9.5 Al and %6.5 C. In addition, if the initial compacting pressure of the powders was decreased to below 100MPa, the SHS reaction did not take place properly.

**Keywords:** Copper Foam, Self-propagation High-temperature Synthesis (SHS), Copper alumina composite

### 1 Introduction

Metal foams have many interesting properties, such as low density, high stiffness in conjunction with very low specific weight and high gas permeability combined with high thermal conductivity [1, 2]. However, since these materials find more applications in the industry nowadays, they need to be studied extensively to characterize all these properties [3].

Many different methods have been used to manufacture metal foams, among which, the methods that use metal powders are the most widely used. These methods have a good control over the cell shape, cell size and porosity distribution. Some investigators have used the Sintering and Dissolution Process (SDP) to manufacture the metal based foams [4, 5], and recently, the Lost Carbonate Sintering (LCS) process became the subject of some research in this area [6].

Another metal powder based method for manufacturing metal foams is Self-propagating High-temperature Synthesis (SHS). The reactions involved in this method are strongly exothermic [7] and therefore, once the reaction starts at the heated zone, the heat of the reaction raises the temperature of the neighboring zones and triggers the reaction in those zones again. Hence, the reaction propagates throughout the specimen rapidly [8]. If these reactions generate a gaseous compound, then the final product would be highly porous. Kanetake and Kobashi [9] used this method to manufacture nickel aluminide intermetallic foam, which had an application in the surgical implants.

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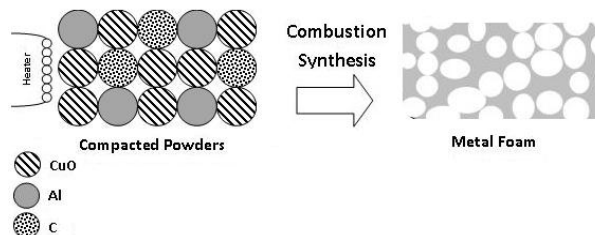
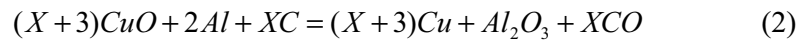
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Copper foam is popular metallic foam, which has been used in various industrial applications, such as thermal conductors, catalysts, and batteries. The Fabrication of porous copper by unidirectional solidification under hydrogen and its properties were investigated by Nakajima et al. [10]. Recently, LCS process was used for manufacturing open cell copper foams [5, 6]. The presence of oxide particles like  $Al_2O_3$  in the copper foam will compound the high electrical and thermal properties of this metal with the strength and the high chemical and thermal stability of the oxide [11]. The use of alumina-copper composite foams in the laboratory reactors has been suggested recently [12].

Aluminum-copper composite can be produced by the SHS method by mixing CuO and Al powders and triggering the reaction by heating it with an external heat source (see Fig. 1):



This reaction produces an enormous amount of heat, and the temperature of the system immediately increases to about 5000 °K [13]. In this temperature, the product of the reaction will be vaporized. Adding graphite powder to the powder mixture will decrease this temperature, and also increase the porosity of the final product by producing carbon monoxide gas:

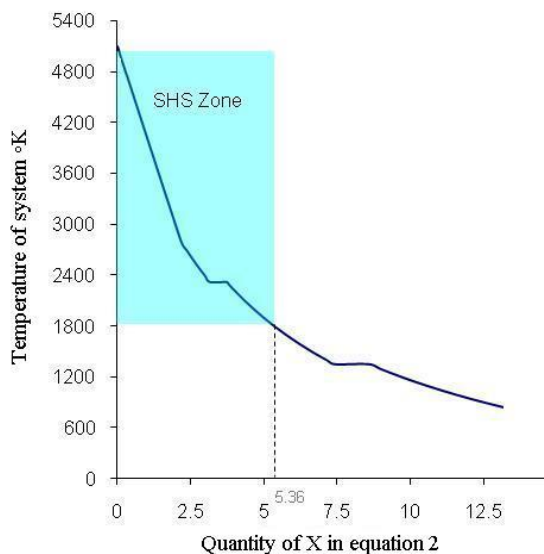


**Fig. 1:** Schematic illustration of the combustion reaction for synthesizing porous materials.

In this reaction, the stoichiometric parameter X can vary between 0 and 6, signifying the C content ranging from 0 to 35.3 mol% in the reactant mixture. Thereupon, the temperature of the system will be determined by X in this equation.

Fig. 2 shows the relation between X and the adiabatic temperature of the system. The minimum adiabatic temperature of the system for the SHS reaction to take place is 1800 °K [14] and hence, according to Fig. 2, the SHS condition would be terminated if X is greater than 5.36.

In this research, the SHS process was adopted to produce copper-alumina composite foam. Porosity, micro and macro structural characteristics are also examined using an optical microscope and Scanning Electro Microscope (SEM).



**Fig. 2:** The relationship between the quantity of X in Eq. 2 and the adiabatic temperature of the system.

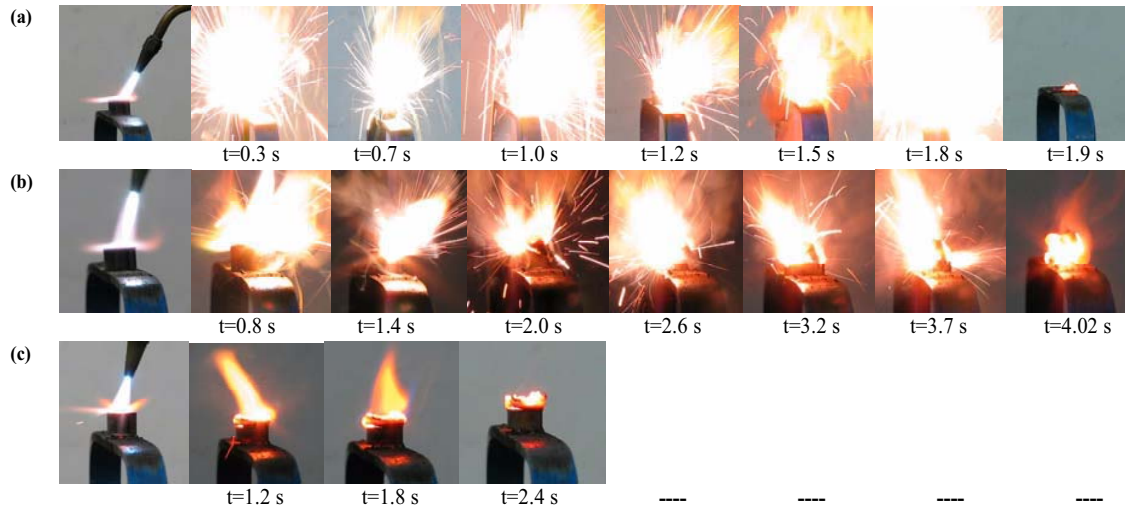
### 3 Experimental procedures

The raw material used in the SHS for manufacturing the composite foam were copper oxide (CuO) (<math><160\ \mu\text{m}</math>), aluminum (<math><45\ \mu\text{m}</math>) and graphite (<math><45\ \mu\text{m}</math>) powders. The powders were evenly blended by a mixer at the molar ratios (quantity of X in Eq. 2) ranging from  $X=0$  to  $X=6$ . The blended powder was then cold-pressed (at room temperature) by different compacting pressures (of between 90 and 250 MPa) in a cylindrical press ( $h = 17\ \text{mm}$ ,  $\text{Ø}=17\ \text{mm}$ ) to make a precursor. The top region of the precursor was then heated by an oxy-acetylene flame to trigger the combustion reaction. After the reaction was completed, the cross-section of the specimen was studied using an optical microscope (OM) and a scanning electron microscope (SEM). The porosity was also measured by the Archimedes method, after the specimens were covered by oil and the extra oil was wiped out.

### 4 Results and discussion

The difference between the severities of the reactions that took place in the different compacts confirmed that the combustion behavior of the reactant compact varied with C content of the initial powder mixture. Fig. 3(a) shows the typical SHS sequence of a compact in which, the molar ratio of CuO : Al : C was 3 : 2 : 0 ( $X=0$ ). It is evident that upon ignition, a distinct reaction front formed and then harshly propagated downwards in a self-sustaining fashion. The severity of the reaction was too high and all the products of the reaction were vaporized. This was attributed to the high adiabatic temperature evolved during the phase transformation. As also revealed in Fig. 3(a), the combustion front traversed the entire sample in about 1.9 s. The severity of the reaction was moderated by introducing C in the reactant mixture. When the C content increased to 27.3 mol% (CuO : Al : C = 6 : 2 : 3 ( $X=3$ )), as depicted in Fig. 3(b), the sample compact retained its original shape throughout the SHS process. This implied that the reactions evolved less adiabatic temperature in the C-containing compact. Moreover, the addition of C also led to a slower propagation of the reaction front. As can be seen in Fig. 3(b), it took about 4.02 s for the combustion wave to arrive to the bottom of the sample. On the other hand, Fig. 3(c), which shows the combustion of a mixture with 33.3 mol% C (CuO : Al : C = 8 : 2 : 5 ( $X=5$ )), showed that increasing the

graphite to  $X=5$  in the reactant mixture caused the SHS process to get terminated before it was completed.


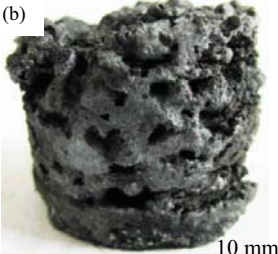
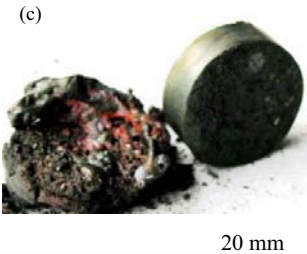
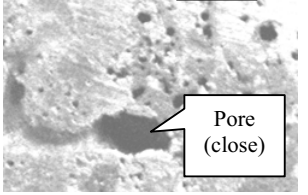
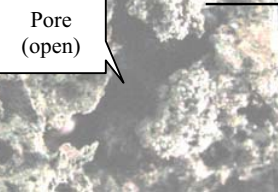


**Fig. 3:** Recorded images of the combustion reaction of the SHS process, with different initial  $X$  in Eq. 2. (a)  $X=0$ , (b)  $X = 3.0$  and (c)  $X=5$ .

The C content of the precursor also influenced the morphology of the pores produced during the reactions. This can be observed in Fig. 4, which shows the appearance of the product and the pore morphology of the combustion synthesized Cu–Al<sub>2</sub>O<sub>3</sub> foams with different blending ratios ( $X=1$ ,  $X=3$  and  $X=5$ ). This parameter controls the fraction of the gaseous phase (CO), which increases the porosity during the combustion process. Therefore, increasing the C content was expected to increase the porosity of the samples. Fig. 4(a) shows the pore morphology of the porous Cu composite with a blending ratio of CuO : Al : C = 4 : 2 : 1 ( $X=1$ ). The micrographs of the cross section of this sample showed spherical closed pores. On the other hand, Fig 4(b) showed that open-pores were formed at a higher C ratio (CuO : Al : C = 6 : 2 : 3 ( $X=3$ ) and again, the combustion reaction of the compact powder was terminated, as the blending ratio reached to CuO : Al : C = 8 : 2 : 5 ( $X=5$ ) (Fig. 4(c)).

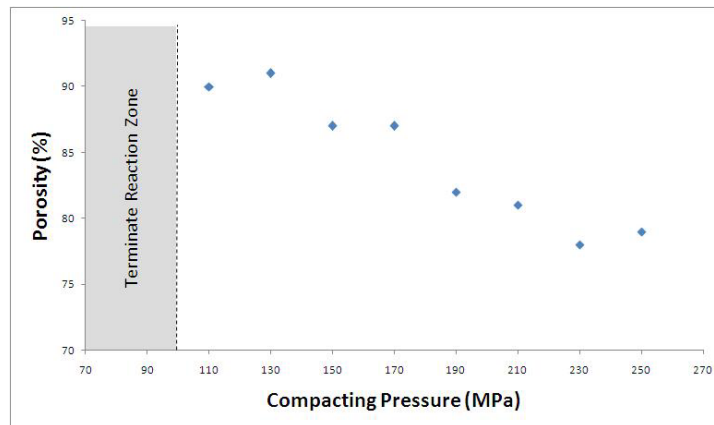
Compacting pressure of the precursor also had a direct effect on the pore morphology, especially when the C ratio was low in the powder compact (the formation of the pores during the combustion reaction was low due to the small fraction of gaseous phase, CO).

Fig. 5 exhibits the porosity of the specimens, the blended powders of which were compacted by different compacting pressures. It can be seen that a decrease in the compacting pressure produced higher degrees of porosity. This result was similar to those of Kanetake and Kobashi [6], who used the SHS process to produce nickel aluminide intermetallic foams. However, the precursors that were produced using a compacting pressure of 100 MPa or less were unstable during the combustion and the SHS process was terminated before it was completed. As the compacting pressure decreased, the intimate contact between the reactant particles was decreased and this consequently decreased the propagation rate of the combustion front.

Appearance	(a) 	(b) 	(c) 
Cross-sections			-----
Quantity of X in Eq. 2	X =1	X =3	X =5

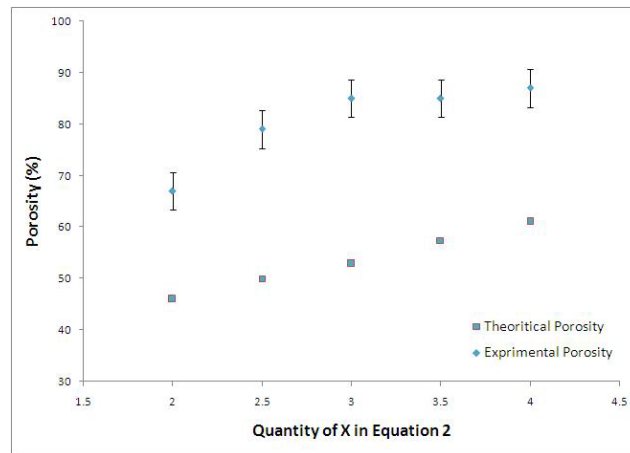
**Fig. 4:** The appearance and pore morphology of the combustion synthesized specimens with X=1, 3 and 5.

The theoretical porosity of the samples were calculated by considering the change of C to CO and also the difference between the molar volumes of the initial and final materials. Fig. 6 shows the theoretical and experimentally measured porosity contents of the different samples with different quantities of X of between 2 and 4. As it can be seen, in all the samples, the experimentally measured porosities were higher than the theoretical ones. This was also observed by Kim [15], who attributed this difference to the release of H content of the Al powder during the SHS process. However, other factors such as the expansion of produced gases during the process might also attribute to these higher porosities.



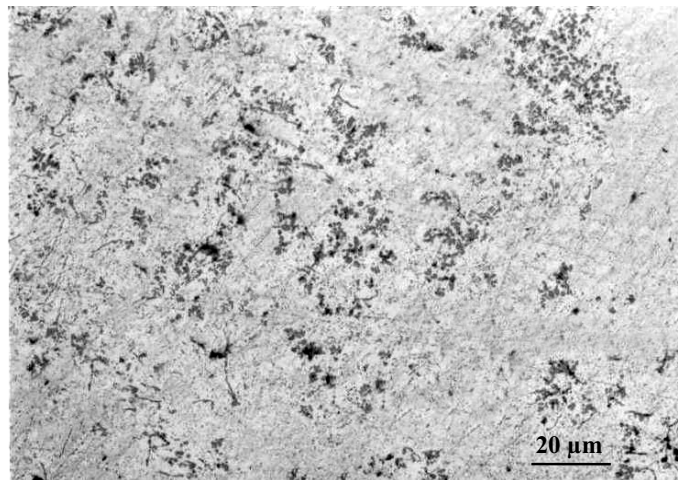
**Fig. 5:** Porosity of the specimens with X=3 and different compacting pressures.

The mechanical, electrical and thermal properties of a metal matrix composite depend on the uniformity of the dispersion of the reinforcing particles in the matrix. Fig. 7 shows the microstructure of the Cu-Al<sub>2</sub>O<sub>3</sub> foam, produced from a powder blend of CuO : Al : C = 6 : 2 : 3 (X=3) and compacted by a pressure of 250 MPa. This figure shows that the microstructure contains alumina particles (black) dispersed (almost) homogeneously in the white matrix of copper.



**Fig. 6:** The theoretical and experimentally measured porosity of the samples compacted by a pressure of 250 MPa.

In summary, the SHS process could be used successfully to produce an open cell porous Cu-Al<sub>2</sub>O<sub>3</sub> composite, with a porosity content of about 90% and an almost uniform microstructure. The best molar powder ratio for this process was found to be CuO : Al : C = 6 : 2 : 3 (X=3). The porosity content of the final product could be changed by changing the pressure by which the initial powder mixture was compressed. However, if this compacting pressure was decreased to lower than 100 MPa, the SHS process could not sustain and was terminated midway, before it was completed.



**Fig. 7:** Microstructure of Cu-Al<sub>2</sub>O<sub>3</sub> metallic foam by X=3.

## 5 Conclusions

Relatively homogeneous Copper-Alumina composite foam was fabricated by the chemical reaction of CuO, Al and C powders, and the following results were obtained:

1. The molar blending ratio of the green ingredients was found to be an important parameter, which controlled the behaviour of the SHS reaction and the porosity content of the final product. The best molar powder ratio for this process was found to be CuO : Al : C = 6 : 2 : 3 (X=3).
2. The compacting pressure of the powder mixture controlled the porosity content of the final product. The less the compacting pressure, the more the porosity of the product.

However, if this pressure was decreased to below 100 MPa, the combustion reaction could not sustain and the SHS reaction was terminated.

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