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Innovative Foaming Processes for Ultra Light Weight Aluminum Foams

Naoyuki Kanetake

Department of Materials Science and Engineering, Nagoya University,
Frochou, Chukusa-ku, Nagoya City, 464-8603 Japan

Porous and cellular metals like aluminum foams have attractive structural and functional properties due to their unique cell morphology. Although the structural application in automotive, aerospace or machine industry is still limited, it will be strongly expected in near future. For the further industrial applications of the metallic foams, the reduction of materials cost is very important as well as the improvement of the homogeneity and reliability of the foams. The foaming process by heating foamable precursor is very convenient for producing complex shape products by die foaming or filling foams into hollow parts. In the precursor foaming process, recently, some innovative processes have been developed to reduce heating energy and an initial material cost. In this paper, some innovative technologies to produce aluminum foams and aluminum/intermetallic composite foams are presented.

Keywords: *Porous metals, Aluminum foams, Powder process, Precursor foaming process, Combustion reaction.*

1. Introduction

Reductions of the vehicle weight and CO_2 in emission gas are strongly required since the concern to the environmental issue increases. Moreover, both the rigidity of the body and improvement in the impact energy absorption are also required simultaneously. Porous metals are regarded as materials which can strike a balance between low density and high rigidity at the same time [1-8]. Among wide variety of porous metals, porous aluminum or foamed aluminum containing many closed pores inside shows some interesting features as shown below [9-15].

- Ultra Lightweight (specific gravity < 1.0)
- High specific stiffness with hollow skin
- High energy absorption
- Low thermal conductivity
- High damping capacity

Some of the foaming technologies are processes by heating foamable precursor which is usually prepared from some mixed powder compaction. Most of the precursor foaming technology uses precursors containing foaming agents, which release some sort of gaseous phase by their decomposition in heating. This process is mostly beneficial to light metals like aluminum alloy because their melting points are not too high to be achieved by the conventional electric furnace. The author and others have developed other precursor foaming technology with the help of a combustion reaction to synthesize intermetallic or metal/intermetallic composite foams [16-18]. Since intermetallic shows better resistance against corrosive environments and higher mechanical properties than metals, the intermetallic foam can be applied to a thermal barrier coating at high temperatures and crash elements with high strength and stiffness.

The precursor foaming technology is very convenient for producing complex net shape products by die foaming or filling foams into hollow parts. In the precursor foaming processes, recently, some innovative technologies have been developed to reduce an initial material cost and heating energy. In this paper, following innovative technologies to produce aluminum foams and aluminum/ intermetallic composite foams are presented.

- Foaming of long foamable precursors by partial heating [19, 20]
- Foaming of precursor made from recycled chip wastes [21, 22]
- Combustion foaming by using chemical reaction [16-18]
- Self-propagation foaming of long precursors [20, 23]

2. Foaming process with the decomposition of foaming agent

2.1 Foaming of aluminum precursor with TiH_2

Fig. 1 shows a schematic illustration of foaming process of an aluminum precursor. The foamable precursor is produced by consolidating aluminum alloy powder containing a foaming agent like TiH_2 with hot pressing, hot extrusion or other compacting methods. Then the precursor is heated above its melting point, the foaming agent decomposes and releases gas, resulting in expansion of the semi-liquid viscous compact and a foam structure containing a large number of closed-pores. This technique has the advantage of the possibility for producing near-net-shape components of aluminum foams. However, in order to put the aluminum foams much more in an industrial use, further improving the foaming process and reducing the materials cost are still important key issues.

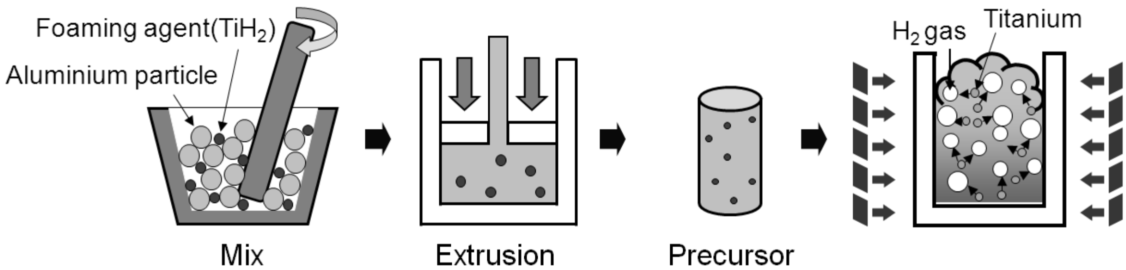

Fig. 1: Schematic illustration of foaming process of aluminum precursor.

2.2 Foaming of long precursor by partial heating

With the precursor foaming technology, large and long foamed products are difficult to produce by heating all over the precursor. New foaming processes were investigated to produce long size foamed products by partial heating of foamable rod precursors [19, 20]. Fig. 2 shows a schematic illustration of partial heating of a rod precursor with induction coil. The precursor was made from aluminum alloy powder and 0.5mass% TiH_2 powder with a hot extrusion. A part of the rod precursors (ϕ12mm×150mm) were heated by a high frequency induction coil heater (coil length = 25mm). The specimen temperature at the center of heating part was monitored with a radiation thermometer. The moving of precursor (or heating coil) was controlled with the monitoring temperature and moving

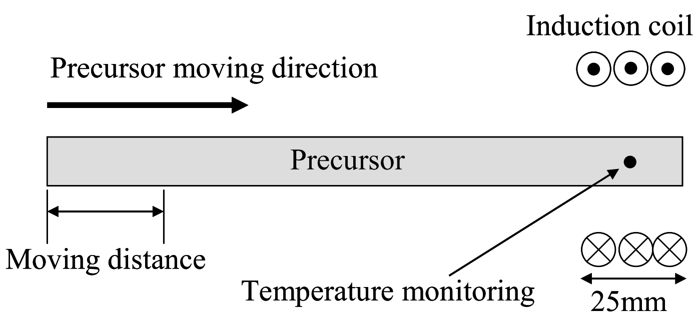

Fig. 2: Schematic illustration of foaming process by partial heating with induction coil.

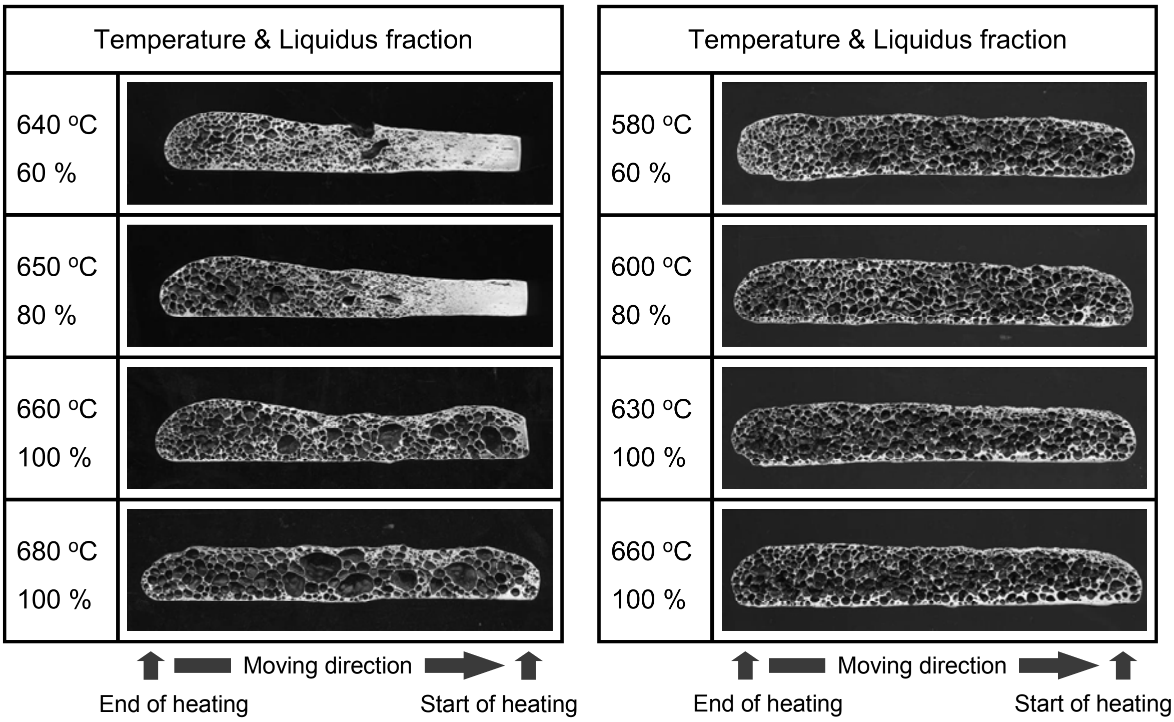

Fig. 3: Longitudinal cross sections of specimens foamed from 6061 (left) and Al-7Si alloy (right) precursors with different control temperature and liquidus fraction.

distance as follows. When the monitoring temperature is reached to a given control temperature, the precursor is moved in a given moving distance along its longitudinal direction to heat next part of the precursor. The temperature monitoring and precursor moving are continuously repeated until heating all over the precursor.

The optimum conditions of moving distance at each step for homogeneous foaming is clearly related with the induction coil length. In the case of the moving distance just about the coil length, the uniform foaming was not obtained but the precursor was discontinuously foamed. In the foaming conditions of a little shorter moving distance than the coil length, the precursor was uniformly foamed along the length of precursor. Fig. 3 shows the cross sections of specimens foamed from 6061 and Al-7Si alloy precursors with different control temperatures. The control temperature was selected concerning with solidus and liquidus temperatures of those alloys, and the liquidus fraction at the control temperature was shown in the figure. In the 6061 alloy precursor, sufficient foaming was not obtained at starting part of heating, but only the ending part of heating was foamed at the control temperatures between solidus and liquidus. At the liquidus temperature or over, the precursor was foamed successfully all over the length though several coarse pores were observed. On the other hand, in the precursor of Al-7Si alloy, well foamed specimens were obtained at wide range temperatures over solidus.

2.3 Foaming of precursor made from recycled chip wastes

For the cost reduction, it is effective to use recycled machined chip waste instead of aluminum powders to produce foamable precursor. The important issues to produce well foamable precursor from machined chips are firm consolidation of chips and homogeneous dispersion of foaming agent in the precursor. In using machined chips instead of aluminum powder, it is quite difficult to blend small TiH_2 powder with machined chips by a conventional method because of a big difference in size and shape of these materials. Furthermore, it is difficult to make firm consolidation precursor from machined chips due to their irregular shape, large size (longer than 10mm in length), and surface contamination with oxides. We have developed new process to produce foamable precursor from machined chip wastes by using a compressive torsion process which is one of severe plastic deformation process [21, 22]. Fig. 4 shows an appearance of the compressive torsion process. In this process, the chips were subjected to severe shear deformation by simultaneous compression and torsion loading under elevated temperature, and then firm consolidated cylindrical precursor is easily produced from machined chip wastes.

In the precursor made from the chips by the hot extrusion process, many chip boundaries were observed along the extrusion direction, which could not be well-consolidated. Furthermore TiH_2 particles were agglomerated at the chip boundaries aligned along the extrusion direction. It was difficult to achieve homogeneous dispersion of the foaming agent in the extrusion process. As a result, pore coalescence occurred easily during the foaming of the extruded precursors. In the precursor produced by the compressive torsion processing, on the other hand, each chip was well bonded and a firm consolidated precursor with no chip boundaries could be fabricated. In this precursor, TiH_2 particles were homogeneously dispersed and no agglomeration was observed like the precursor produced from powder alloy.

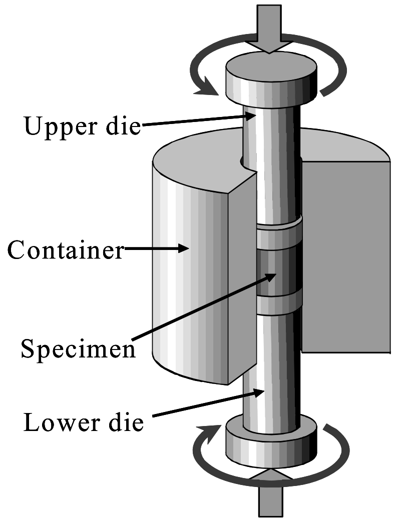

Fig. 4 Schematic illustration of apparatus for compressive torsion processing.

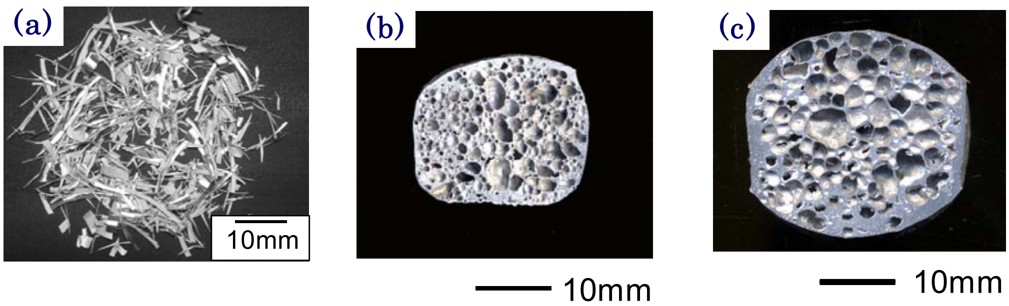

Fig.5 (a) Appearance of Al-Mg-Si alloy machined chip wastes, and cross sections of foamed aluminum made from (b) machined chips and (c) powder alloy.

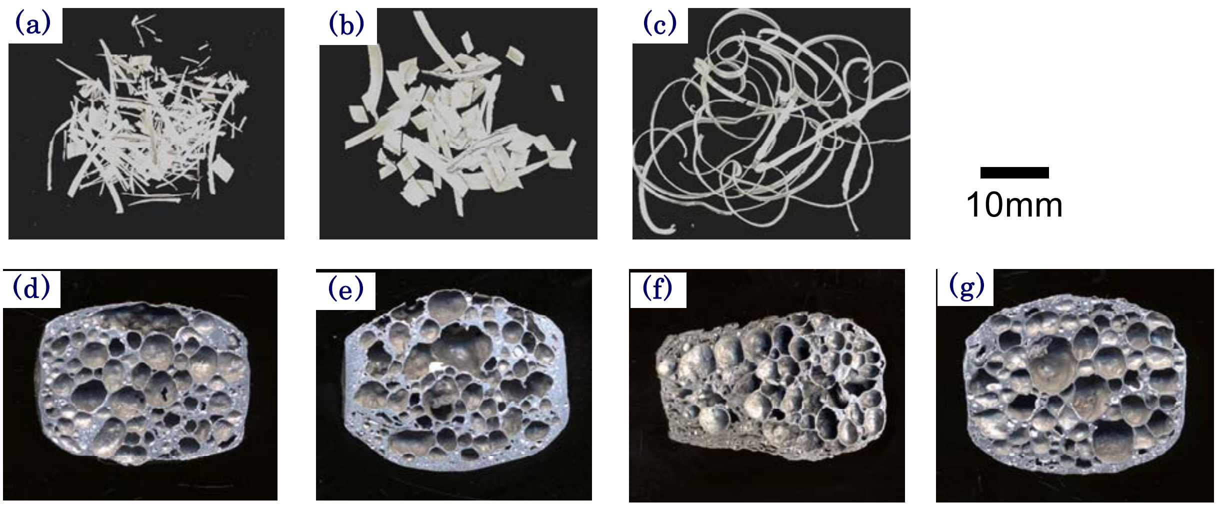

Fig. 6 Cross sections of foamed aluminum made from different shape chips precursors. (d) to (f) are made from chips (a) to (c) respectively and (g) is from mixed chip of (a) to (c).

Fig. 5 shows an example of Al-Mg-Si alloy machined chip wastes and the cross section of the specimen foamed from the chips precursor produced by the compressive torsion processing together with one from a powder extruded precursor. The porosities of both foamed specimens were around 75% and the size and shape of their pores were similarly uniform. Fig. 6 shows the cross sections of the specimens foamed from precursors produced from different shape of chips shown in the figure. Their shapes are quite different from thin chips to long string type waste. Similarly foamed specimens were obtained from quite different shape chips, and sufficiently foamed specimen was obtained even from a mixed precursor with three different shape chips. All foams have almost the same porosity of around 75%. The compressive torsion process is very useful to produce a foamable precursor from various shapes of machined chip wastes from a viewpoint of both firm consolidation of a precursor and homogeneous dispersion of the foaming agents.

3. Foaming process with the combustion reaction

3.1 Foaming of Al/Ti or Al/Ni mixed precursor

Combustion synthesis is one of the attractive processing routes for producing intermetallics and their composites because high-melting-point material can be produced with little energy and without special equipments [24, 25]. Fig. 7 shows a brief outline of the combustion foaming process for the synthesis of Al/Al_3Ti or Al/Al_3Ni porous composites. Those composite foams were fabricated by heating a reactive precursor consisting of aluminum, nickel, titanium and boron carbide (B_4C) powders. Fundamentally, the reactions between elemental powders (Al+Ti or Al+Ni) shown below are used in this technique,

$$3Al + Ti \rightarrow Al_3Ti + 146\ \text{kJ/mole Ti}\ , \quad (1)$$

$$3Al + Ni \rightarrow Al_3Ni + 151\ \text{kJ/mole Ni}\ . \quad (2)$$

As shown in Fig. 7, boron carbide (B_4C) powder is blended in the powder compacted precursor. The B_4C powder reacts with titanium, and generates large amount of reaction heat as shown in the

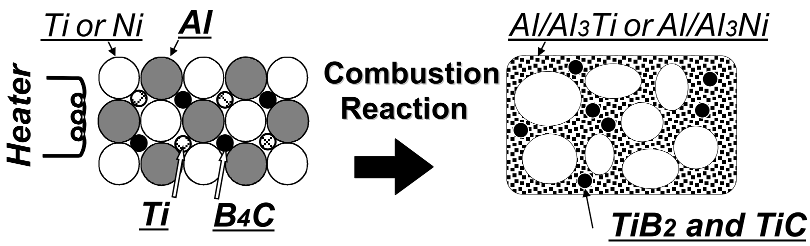

Fig. 7 Schematic illustration of the combustion synthesis of Al-Ti or Al-Ni foams with exothermic agent.

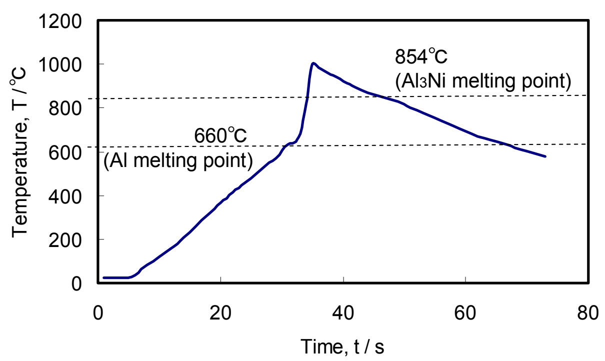

Fig.8 Temperature-time profile of Al-Ni precursor during heating process.

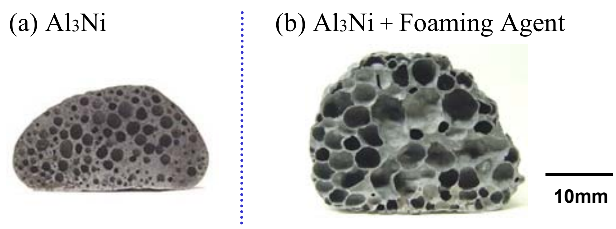

Fig.9 Cross section of Al_3Ni foam (a) without and (b) with exothermic agent addition.

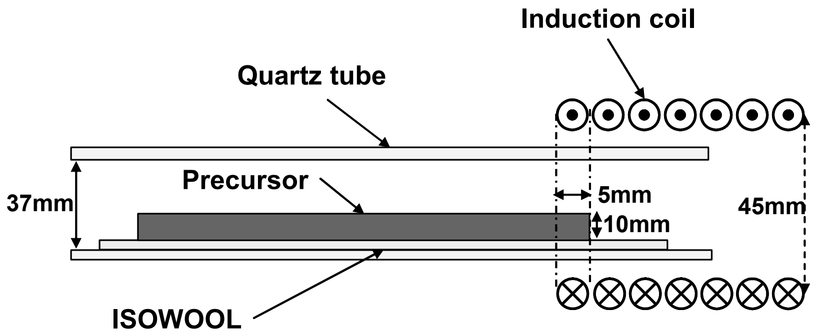

Fig. 10 Schematic illustration of combustion foaming process by partial heating.

following equation,

$$Ti + 1/3B_4C \rightarrow 2/3TiB_2 + 1/3TiC + 254\ kJ/mole\ Ti\ . \tag{3}$$

This heat of reaction assists the progress of the Al_3Ni and Al_3Ti formation and is expected to enhance the foaming behavior. Therefore, B_4C and equivalent amount of titanium, which is required for Eq. 3, were used as the "exothermic agent" in this process.

Fig. 8 shows the temperature-time profile of Al-Ni precursor (Al/Ni ratio: 3.0) during heating process. It is apparent that the reaction started at around the melting point of pure aluminum (660^{o}C), and the temperature exceeded the melting point of Al_3Ni (854^{o}C). Fig.9 shows the cross section of Al-Ni foam (Al/Ni ratio: 3.0) with and without addition of exothermic agents. The cross section of the specimen without agent (Fig.9 (a)) shows spherical pores (average pore diameter: 1.36mm) and the porosity of this foam was 37%. On the other hand, in the specimen with an exothermic agent addition (5 vol%) shown in Fig.9 (b), the cell morphology turned to be less spherical surrounded by thin cell walls. The porosity of this specimen (82%) was obviously improved by adding agents, and the average pore size became larger (2.73mm).

3.2 Self-blowing of long precursors assisted by exothermic reaction

The advantage of the combustion foaming process is that the energy to make foamed materials is not necessarily supplied from the external source, but generated from inside of the precursor (heat of reaction). Therefore the blowing process can be self-sustainable and self-propagation of the blowing process is possible by heating only a part of precursor [20, 23].

Fig. 10 shows an experimental example to investigate the self-propagation foaming by an induction heating. When a part of rod precursor made from Al, Ni, Ti and B_4C mixed powder was heated from room temperature, a pore formation was not satisfactory at the center of the specimen, though the pore formation was observed not only at heated part but also at non-heated part of the precursor. In this case, the rapid temperature rise which means occurrence of the combustion reaction was observed at the

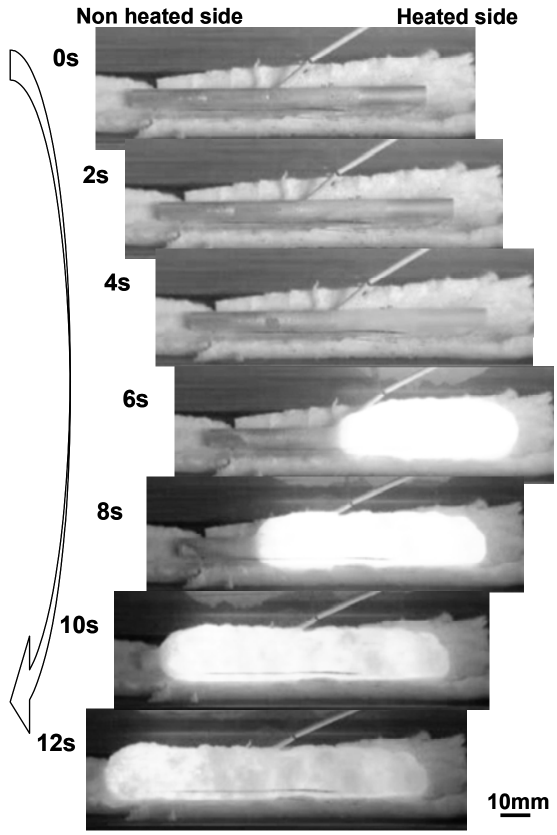

Fig.11 Self-propagation of the blowing process in the specimen preheated at 650^{o}C.

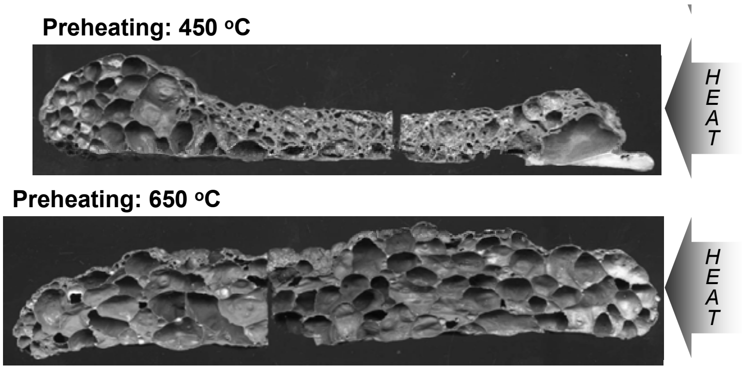

Fig.12 Cross sections of the specimens foamed by combustion process after preheating at different temperatures.

heated and non-heated parts, but temperature rise is not high enough at the center of the precursor.

The precursor was preheated before setting in the induction heating apparatus and the ignition is started immediately after the setting. Fig. 11 shows how the reaction and expansion propagates through the specimen. Fig. 12 shows the cross sections of specimens partially heated after preheating at different temperatures. Although the pore formation is not satisfactory at the center of the specimen preheated at below 450^{o}C, the precursor preheated at 650^{o}C (just below the ignition temperature) was successfully foamed all over the length. After the self-propagation of the blowing process, the specimen with high porosity (92% porosity) is obtained.

4. Summary

Although the metallic foams are regarded as ultra light weight structural materials, their application in automotive, aerospace or machine industry is still limited. The foaming technique by heating foamable precursor is very convenient for producing complex shape products by die foaming or filling foams into hollow parts. In the precursor foaming techniques, recently, some innovative technologies have been developed to reduce heating energy and initial material cost. An initial materials cost will be significantly reduced by using recycled materials like machined chip wastes. The foaming technique of a long rod precursor by partial heating is very effective to reduce size of a foaming equipment. Heating energy for foaming will be saved by using assistance with exothermic reaction.

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