JOURNAL OF MATERIALS SCIENCE 18 (1983) 1899–1911

Review
Metallic foams: their production, properties and applications

G. J. DAVIES, SHU ZHEN*
Department of Metallurgy, University of Sheffield, Mappin Street, Sheffield, UK

Techniques for the preparation of metallic foams, including casting, powder metallurgy and metallic deposition, have been reviewed. Properties of metallic foams such as mechanical properties, energy absorbing characteristics, permeability, acoustical properties and conductivities are described. Finally, examples of the use of metallic foams in practice have been given to indicate the wide range of circumstances in which metallic foams are able to be utilized.

1. Introduction

In the last two decades metallic foams (porous metals with high porosity ranging from 40 to 98 vol%) have been developed and are growing in use as new engineering materials. These exceptionally light weight materials possess unique combinations of properties, such as impact energy absorption capacity, air and water permeability, unusual acoustic properties, low thermal conductivity and good electrical insulating properties. Their applications include shock and impact absorbers, dust and fluid filters, engine exhaust mufflers, porous electrodes, high-temperature gaskets and abradable seals, heaters and heat exchangers, flame arresters, catalyst supporters, etc. The field of applications of metallic foams is growing steadily.

There are many methods available to produce metallic foams [1]. Early attempts concentrated on foaming techniques, similar to those used for plastics, with gas serving as the blowing agent. Another method produced an interconnected cellular structure by using granules, which can be incorporated into the melt or introduced into a casting mould. Metallic foams can also be produced by metallic deposition on reticulated urethane substrates [2]. Some powder metallurgy techniques including slurry foaming, loose powder sintering and fibre metallurgy have been used for the production of high porosity metals. More recently, sputter deposition has been used to produce metallic foams [3]. Fig. 1 gives a summary of the methods used to produce metallic foams.

In this review it is intended systematically to describe the methods of manufacture and the properties and applications of metallic foams. A brief outline of the directions of future developments will also be given.

2. Methods of producing metallic foams
2.1. Casting
2.1.1. Foaming techniques

An initial proposal by Sosnik [4] in 1948 was concerned with using the vaporization of mercury in aluminium for foamed aluminium. Elliot [5] subsequently developed this idea and successfully produced foamed aluminium in 1951. According to the process, foamed metals are produced by adding a blowing agent to a molten metal and heating the mixture to decompose the blowing agent to evolve gas. The gas expands causing the molten metal to foam. After foaming, the resultant body is cooled to form a foamed solid. Usually the blowing agent is a metal hydride such as TiH_2 or ZrH_2, and the metal to be foamed is aluminium although other flowing agents and other metals may be used. This process was rather difficult to control and the foamed metal produced had a

---

*On leave from Department of Mechanical Engineering, Hunan University, China.

0022–2461/83 $03.00 + .12

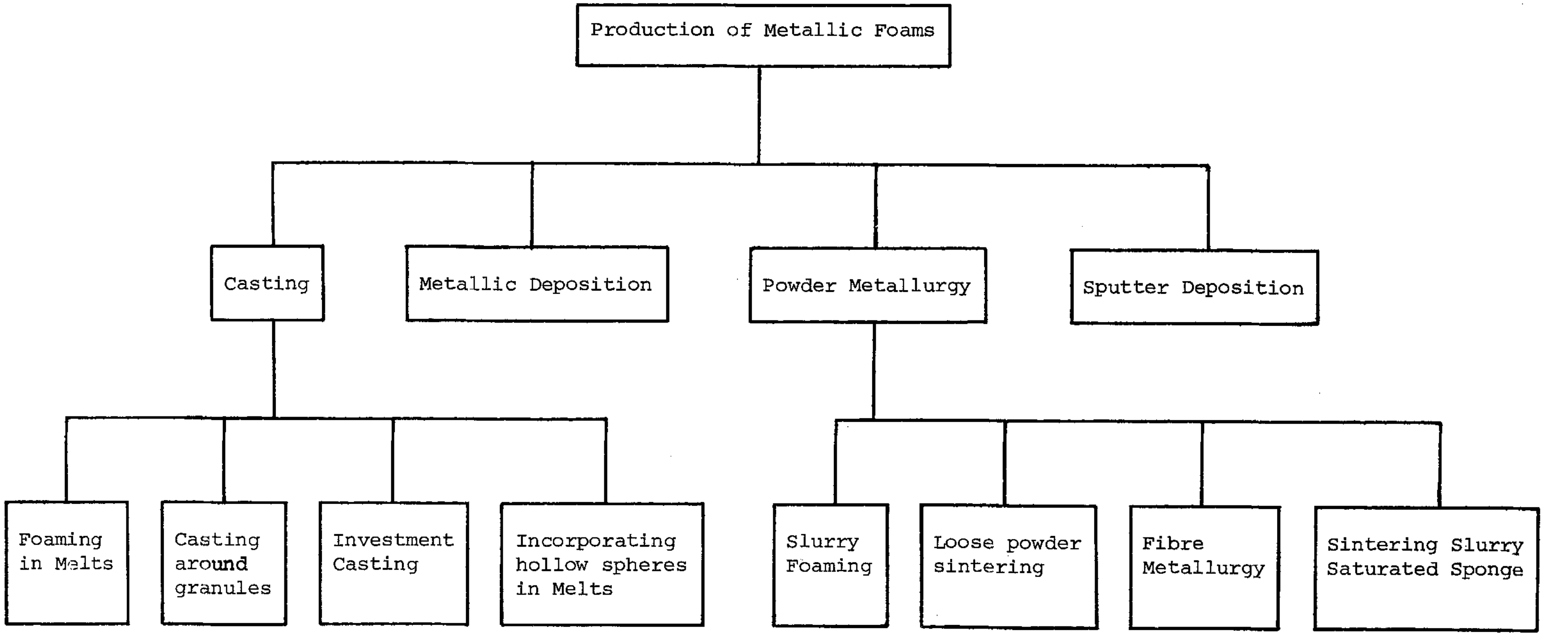

Figure 1 The methods of producing metallic foams.

non-uniform cellular structure. Large gas bubbles were concentrated at the centre and there was increasing density near the chilled surface. In order to overcome these problems, various improvements have been made.

The problems of the non-uniformity of distribution and undesirable large size of some cells have been treated in several ways. Firstly, by using high speed mixing (with stirring rates as high as 10 000 rpm) particles of the foaming agent can be dispersed throughout the molten metal mass in a very short time, as low as 10 sec [6]. Without exception it was observed that the more uniform the mixing, the better the foam. Secondly, increasing the viscosity of the molten metal can aid in the subsequent blowing step, preventing the escape of bubbles. This can be done by utilizing alloys with a wide difference (200 to 400° C) between the alloy solidus and liquidus temperatures [7]. However, the introduction of a viscosity-increasing agent into a molten metal mass is more applicable. The viscosity-increasing agents which are used can be either solids, liquids, or gases, such as siliceous non-metallic aggregate [8], dross [9], air, oxygen, nitrogen, carbon dioxide, argon and water [6]. When molten metals are treated with a viscosity-increasing agent a much thicker melt is produced. In foams produced by thickening followed by foaming the pore size is smaller and more uniform. If degassing of the foam is carried out subsequent to the addition of the thickening gas, the foamed metal is observed to have a more uniform pore structure [10]. In addition, for zinc foams using sequential expansion can lead to better results [11]. This can be achieved by making more than one addition of blowing agent to the molten metal, or by applying agitation to collapse the foam and allowing it to expand again, or by foaming with an intermediate product. Finally, with aluminium, adding a particulate solid oxidizing agent, such as MnO_2, to the molten mixture can result in the provision of foam having greater uniformity of cell size, cell distribution and cell shape because of the formation of cell nuclei of Al_2O_3 particles [12]. Generally speaking, the non-uniformity and undesirable size of cells in foamed metals can now be avoided because of the above improvements.

Another problem arises because of the relatively short time interval between adding a foaming agent to the molten metal and foam formation. This makes the casting operation particularly difficult. Thickening is one means of enabling the foamed metal to be maintained in its heated, fluid condition for relatively prolonged periods without collapsing. Another expedient is to use a continuous method of preparing and casting the liquid material [13, 14]. For batch operations, an improved vessel, in which the mould bottom serves as the bottom of the mixing vessel, can be used to achieve a very rapid transfer of castable liquid material from the container in which it has been prepared, into the mould [15]. Finally, the onset of the decomposition of the metal hydride can be controlled by heating an admixture of a discrete particulate flowing agent and a discrete particulate material containing a major proportion of aluminimum, in the temperature range 450 to 480°C for at least five minutes to form a surface oxide barrier layer on the particles of the metal hydride [16]. All of these improvements impart greater practicality and convenience to the foaming operation.

2.1.2. Casting metal around granules

This method produces an interconnected cellular structure or sponge metal by casting metal around granules introduced into the casting mould. These granules can be soluble (but heat-resistant), such as sodium chloride (ordinary table salt) which is later leached out to leave a porous metal [17]. Granules can also be some loose bulk of an easily compressible inorganic material such as expanded clay, foamed glass spheres, hollow corundum spheres, etc. [18–20].

However, the surface tension of most metals, especially aluminium, prevents the metal melt from immediately flowing into the interstices. This can be overcome by producing a slight vacuum in the bulk or by exerting a slight external pressure upon the melt. In addition, some superheating of the melt or preheating of the granules can be used to advantage. This process has been used not only with aluminium, but also with magnesium, zinc, lead, tin and cast iron, and it allows casting of parts with intricate shapes.

2.1.3. Incorporating granules in the melt

As an alternative to casting molten metal around them, granules can also be incorporated into metal melts. In this process, the metal is melted in a crucible and the granules are introduced therein. The mass is vigorously mixed to disperse uniformly the granules in the metal mass. While the mixing is continued, the mass may be permitted to cool until the mixture is sufficiently viscous as to prevent segregation or stratification. Then mixing is discontinued and the mass is permitted to solidify with the granules embedded. If so desired, before the mass solidifies, and while it is still in a relatively fluid, although viscous, condition it may be cast into a suitable mould [21].

A related technique utilizing hollow metallic spheres that can be incorporated in the melt has been developed in the USA [1]. Commercially available phenolic plastic microballoons are utilized which are heated in an inert atmosphere until the plastic cokes, forming hollow carbon microspheres. The carbon spheres are then coated with metal by vapour deposition and the carbon is removed by vaporization leaving the hollow metal microspheres. This process is most applicable to refractory metals. For example, tungsten can be made into microspheres 60 to 80 μm in diameter, with a uniform wall thickness of 2 μm.

2.1.4. Investment casting

In Japan a unique investment casting technique has been used to produce metallic foam [22]. In this process, voids of a spongy foamed plastic are filled with fluid refractory material which is then hardened. Then, the integral plastic–refractory material is heated so as to vaporize the plastic component and a mould having spongy lattice pores is produced. Molten metal is poured into this mould and allowed to cool and solidify. The refractory is then removed and a metallic foam having the same sponge form as the original spongy plastic is obtained. The metals which have been utilized in this process are those having comparatively low melting points, such as copper, aluminium, lead, zinc, tin and their alloys.

2.2. Metallic deposition

This makes use of a metallization process to apply a metallic cover to polyurethane strands. Basically, the process consists of three stages, rigidization, electroless preplating and electroplating [2]. Rigidization is used to coat the polyurethane foam with a thin epoxy layer to provide the necessary rigidity. Since the foam is only readily available in flexible form, it must be made more rigid prior to metallic deposition in order to avoid distortion of the metal shape produced. After rigidization, the urethane foam surface is made slightly conductive by electroless deposition of a thin metal film. As a preparation for this the surface must be treated with a strongly oxidizing acidic solution (such as a chromic/sulphuric/phosphoric acid mixture) which converts the surface to the water-receptive condition and selectively etches it to produce micro-roughening. This provides a mechanical key to improve the adhesion of the subsequently-deposited metal layers. The surface is then catalysed with palladium from a palladium chloride solution. After that a continuous deposit can be obtained by immersion in an electroless plating solution [23, 24]. Metals that can be deposited in electroless plating are copper, nickel, iron, silver, cobalt, gold and palladium. Of these, copper and nickel are the most widely used. In the final operation, the preplated urethane foam is electroplated to the desired thickness. Those metals and alloys (and the respective plating baths) which have been used are copper (pyrophosphate), nickel (sulphamate), zinc (cyanide), lead–tin (fluoborate) and silver (cyanide). If so desired, the urethane substrate can be subsequently removed by thermal decomposition.

Metal foams produced by metallic deposition (e.g. Retimet, a skeletal foam) are characterized by their exceptional uniformity and high degree of porosity. However, their high cost is apt to restrict their applications.

2.3. Powder metallurgy

2.3.1. The slurry foaming technique

The process starts by preparing a slurry consisting of a fine metal powder and a foaming agent dispersed in an organic vehicle [25]. The mixture is whipped into a foam and then fired to create a solid, porous structure. This technique was developed with beryllium powders and powders of more common metals such as nickel, iron and copper as well as with stainless steel and bronze powders. Since aluminium is an inexpensive metal with many attractive properties, this process has also been used for producing foamed aluminium [25, 26]. In order to produce foamed aluminium, a slurry consisting mainly of fine aluminium powder and a blowing agent, which can be hydrochloric acid, aluminium hydroxide or orthophosphoric acid, is prepared. After mixing the slurry is poured into moulds to form the required shapes. When foaming has subsided, the foams are cured for 2 h at a temperature of the order of 100° C to impart strength and improve the mechanical properties of the foams. Sintering is not used for aluminium powders because of the aluminium oxide which exists at the temperature of sintering. Therefore, aluminium foam produced by the slurry technique has a relatively low strength, which limits its application [25].

2.3.2. Loose powder sintering

According to mechanisms of sintering, contacts between powders particles are established and grow by the action of capillary or surface tension forces during the time that the powder particles are being heated in contact with each other. Application of pressure is not necessary for sintering. Therefore, the metal powder can be used to fill a mould and then sintered. This process is called loose powder sintering [27, 28]. The principal technological applications for loose powder sintering are in the manufacture of porous metallic materials, such as bronze filters, and porous nickel membranes used as electrodes for alkaline storage batteries and fuel cells. The porosities of the materials produced by this technique are from 40 to 60 vol %. In order to achieve high degrees of porosity, the most commonly used means is the addition to the charge of a spacing agent, which decomposes or evaporates during sintering or is removed by sublimation or dissolution [28]. In the manufacture of filters from iron, nickel or copper and their alloys the spacing agent is frequently ammonium tetrachloride. For nickel membranes having high porosities of up to 70 to 90%, commonly methyl-cellulose, in quantities up to 40 vol % is added to the nickel powder as a spacing agent.

2.3.3. Sintering slurry saturated sponge

In powder metallurgy sponge-like materials can also be used as a temporary support structure for producing uniform high porosity metallic foams [29, 30]. A sponge-like organic material, such as a natural or synthetic plastic sponge, is cut to the desired shape and then saturated or soaked with a slurry containing the desired metal powder, the slurry vehicle being, for example, water or an organic liquid. The saturated sponge is then dried to remove the vehicle and the resulting dried saturated sponge is heated to a temperature sufficiently high to decompose or to pyrolyse the organic sponge-like material. The inorganic residue is further heated at a still higher temperature for sintering following removal of the decomposed organic material. After cooling a highly porous structure with interconnected pores is obtained.

In an alternative process a metal compound is used instead of metal powder [31]. The metal compound, such as metal lactic acid salt or 2-hydroxycarboxylic acid salt, can be converted to the corresponding metal by heating to its decomposition temperature when simultaneously the support structure is destroyed by combustion. This process has been used to produce a silver plate with porosity of 70 to 90 vol %.

2.3.4. Fibre metallurgy

Using metal fibres instead of metal powders in producing porous material, especially filters, has some advantages [28], namely:

(i) porosity can be controlled within very wide limits, from 0 to 95 vol % of pores, with the materials retaining their constructional properties even at the highest porosity;

(ii) high strength and ductility can be obtained surpassing several-fold at any given porosity the corresponding properties of materials produced from metal powders;

(iii) high permeability combined with good stopping power can be developed.

Fibre metallurgy involves the preparation of metal fibres of ferrous or non-ferrous alloys by machining, drawing and/or other techniques. These are then processed into felts by slip casting or mechanical felting followed by sintering to develop the required strength and porosity [32]. Filters can be manufactured from various kinds of metal, such as strainless steel, copper, nickel, Ni–Cr alloy by this technique. Because of their unique properties and the development of new, more economical methods of manufacture of metal fibres, interest in porous metal fibre materials has grown considerably in recent years.

2.4. Sputter deposition

A new method to prepare foamed metals having a closed cellular structure has also been developed in the USA [4]. According to this method, a metal body containing atoms of entrapped inert gas evenly distributed throughout is prepared by sputtering the metal under a partial pressure of inert gas, onto a substrate. Then the metal body obtained is heated to a temperature above the melting point of the metal for a period of time sufficient to permit the entrapped gas to expand and form individual cells. After cooling a metal foam body having a closed cellular structure is obtained.

Sputter deposition is the most effective method presently known for preparing metal bodies containing inert gas. The preferred sputtering device is a triode sputtering apparatus in which the plasma is formed independently as the positive column of a discharge maintained between a thermionic cathode and an anode and which has a cooled substrate with a controllable negative bias. The amount of entrapped gas in the sputtered body is generally controlled by varying the pressure of the inert gas in the deposition chamber, the temperature of the substrate and the amount of negative bias voltage placed on the substrate. The entrapped gas content can vary from 15 to 2300 ppm and the formation of void volume fractions in metal from several per cent up to about 80 vol % can be achieved. This method can be used to prepare foams from any material (including non-metallic material) which can be sputter deposited to form a body containing uniformly distributed entrapped inert gas.

3. Properties of metallic foams

The properties of metallic foams greatly depend on the characteristics of the pores distributed throughout them. These characteristics, which include the type, shape, size, number (volume percentage), uniformity and surface area of the pores, may be quite different in foamed metals produced by different processes, thus resulting in different properties of the materials. For example, pores are essentially spherical and closed in the foamed metals produced by foaming in melts, leading to a higher degree of energy absorption [33], while interconnected pores form a highly useful pore maze for materials requiring controlled characteristics of permeability.

3.1. Mechanical properties

The mechanical properties of metallic foams are largely determined by their density. However, the pore size, pore structure and distribution are also important parameters determining the properties. As a general rule, there is a fairly close relationship between density and mechanical properties such as compressive strength, though these properties fall off more rapidly than does the density itself. For example, foamed tungsten, with a density of about 30% of the theoretical density, will show tensile and compressive strengths only 4 to 5% of those of the solid metal [1]. Therefore, property values of metallic foams must be determined for the specific material with the density under consideration.

For a sintered nickel foam (with trade name Foametal) supplied in the annealed condition, the tensile strength at low-density (with 95% or higher porosity) is such that it cannot be considered for tensile loading. Higher-density samples (with less than 80% porosity) show the following tensile strength values: 20% density (expressed in terms of parent metal density) material, 4.8 $\mathrm{N\,mm^{-2}}$ (700 $\mathrm{lb\,in^{-2}}$), 50% density material, 15.9 $\mathrm{N\,mm^{-2}}$ (2300 $\mathrm{lb\,in^{-2}}$) and 60% density material, 19.0 $\mathrm{N\,mm^{-2}}$ (2750 $\mathrm{lb\,in^{-2}}$) [34].

For aluminium foams produced by foaming in melts, typical compression curves are shown in Fig. 2. The variations of the flow stress, lower and upper yield points as a function of density are shown in Figs. 3, 4 and 5, respectively [35]. In all cases, the flow strengths increase more rapidly than linearly with density. In addition, the results emphasize a discrepancy between the mechanical response of the foams and the bulk alloys. Over the comparable range of densities the Al–7%Mg foam is stronger than the 7075 Al-alloy foam. The bulk 7075 alloy is, however, considerably stronger than the bulk Al–7%Mg alloy, the yield stresses being approximately 344 $\mathrm{N\,mm^{-2}}$ (50000 $\mathrm{lb\,in^{-2}}$) and 206 $\mathrm{N\,mm^{-2}}$ (30000 $\mathrm{lb\,in^{-2}}$), respectively. This is because the different foams collapse by different modes with localized fracture becoming dominant in the higher strength 7075 alloy [35].

Foamed aluminium does not have sufficient strength for some commercial uses. Several methods have been suggested to improve the strength characteristics of foamed aluminium. The use of certain thickening agents (usually oxygen containing agents) causes the foamed product to be strengthened with a metal oxide formed *in situ* [36, 37]. By using as much as 30% scrap foamed aluminium (when melting), a foamed aluminium body of substantially increased strength can be obtained [38]. Solution heat treatment and ageing heat treatments can also be used for aluminium foams alloyed with copper, magnesium, zinc or silicon [39]. However, the greatest improvement in strength has been achieved by adding reinforcing fibres to metal foams [40, 41]. The mechanical strength of a reinforced aluminium foam is many times higher than that of conventional aluminium foams.

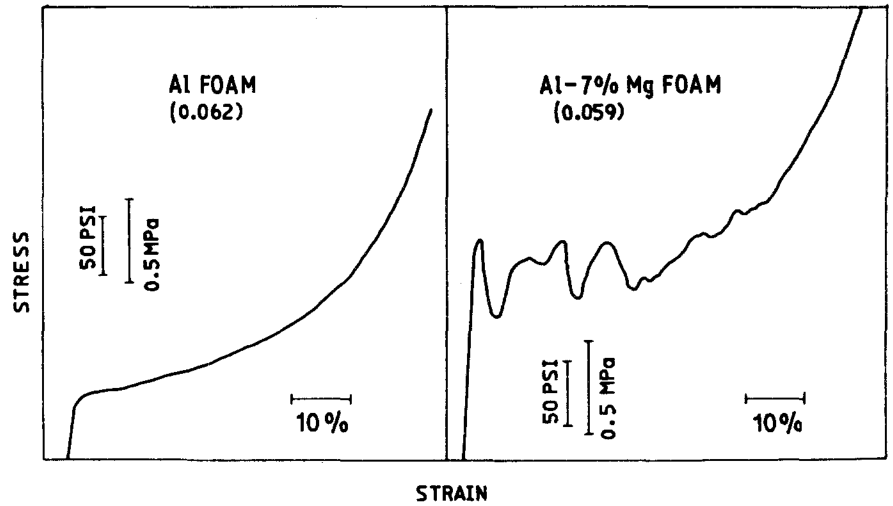

Figure 2 Flow stress curves for as-cast aluminium and Al–7% Mg foam [35].

3.2. Energy absorbing characteristics

The energy absorption capacity (the energy absorbed per unit volume) is simply given by the area under the stress–strain curve. The energy necessary to deform as-cast aluminium foam specimens either 25, 50, or 70% is shown in Fig. 6 [35]. It is seen that the energy absorption capacity also increases more rapidly than linearly with density. This is because the deformation resistance of aluminium foam increases more rapidly than linearly with density.

For sponge-like aluminium with inclusions of expanded clay mineral of different grain sizes the compression curves obtained during deformation are shown in Fig. 7. The energy absorption capacity of aluminium-based sponge materials up to a compression deformation of 50% ranges from 6850 to 39200 kJ m^{-3}. As may be seen from Fig. 7, the grain size of the filler and, hence, the density of the sponge-like metal have a distinct effect on the compression behaviour of this material. The deformation resistance can be increased from five to six times the original value by selecting a filler of the proper grain size or by using a suitable metal alloy.

Some foamed metals made from brittle or high strength alloys and metal foams of high density compress only to about 10 to 20% and exhibit

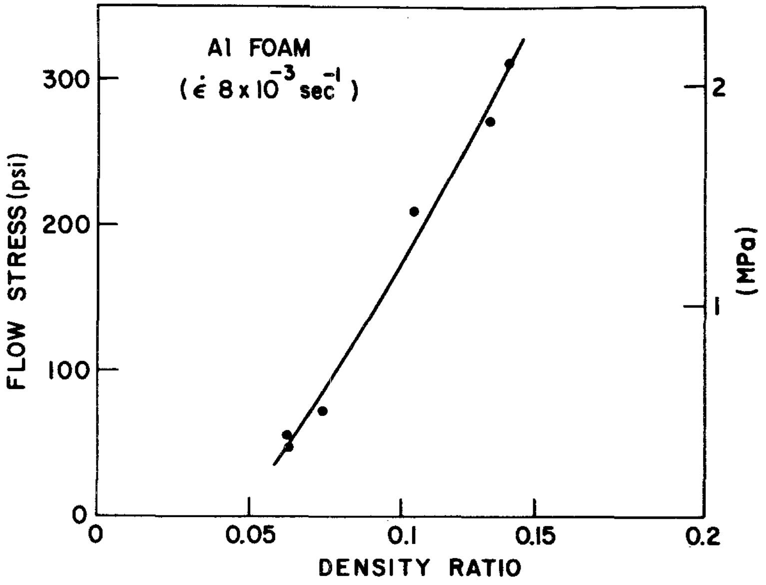

Figure 3 The variation of flow stress with density ratio for aluminium foam [35].

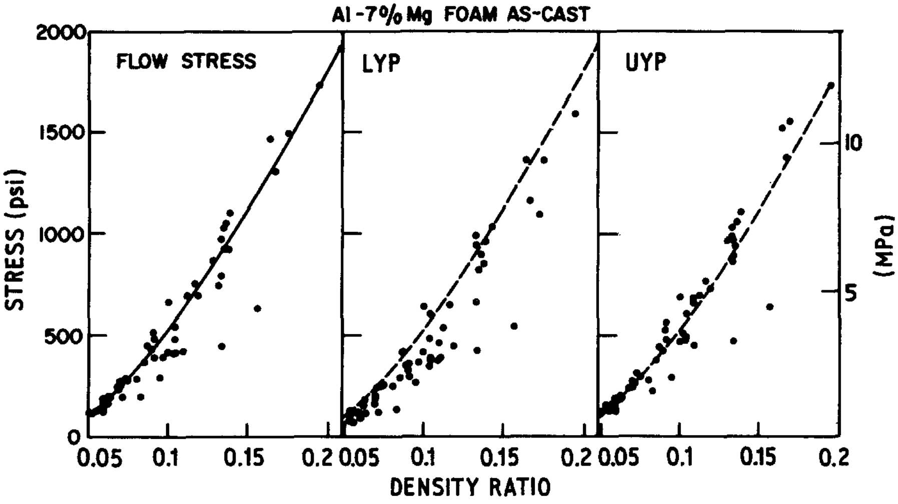

Figure 4 The variation of flow stress, LYP and UYP with density ratio for as-cast Al–7% Mg foam [35].

catastrophic shear on impact [42]. This problem can be solved by the use of a laminated structure comprising of a multiplicity of foamed metal layers having a sheet material interposed between the layers. The sheet material, preferably aluminium, acts to distribute the applied force. Reinforced in this way, foamed aluminium does not shear catastrophically but compresses through as much as 65% of the original structure height.

3.3. Permeability

Permeability is the key property of high-porosity materials for a variety of purposes such as filtration, liquid–liquid separation, noise attenuation, etc. The permeability generally increases with an increase in pore size. It is also affected by the surface roughness of the pores and is greatly influenced by the number of closed pores in the foam. Only these metallic foams with open pores possess high permeability.

The fluid permeability of a permeable metal material can be determined experimentally. That is, the pressure drop and the volumetric flow rate are measured when a test fluid of known viscosity and density is passed through a test sample. Then a permeability coefficient can be calculated using Darcy's equation [27]:

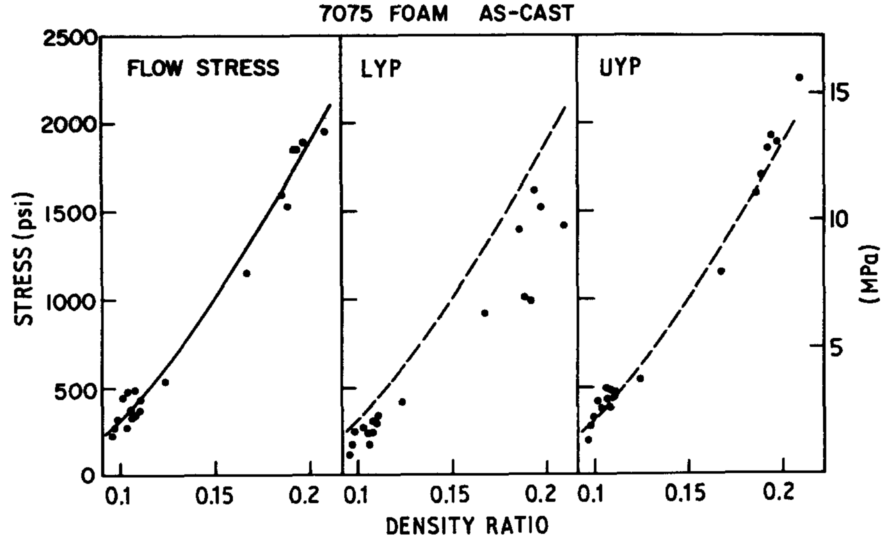

Figure 5 The variation of flow stress, LYP and UYP with density ratio for as-cast 7075 Al-alloy foam [35].

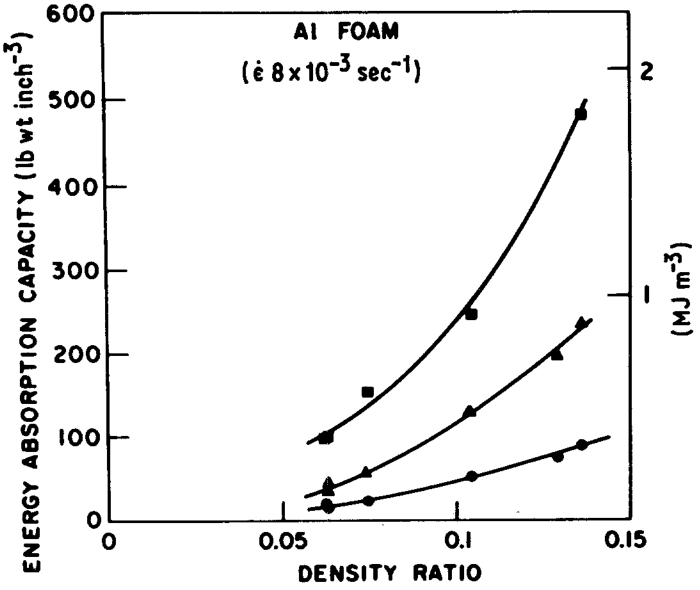

Figure 6 The variation of the energy absorption capacity of aluminium foam in various heat treatment conditions with change in density [35].

$$\frac{\Delta p}{t} = \frac{Q\mu}{A\psi_V}$$

where Δp is the pressure drop in N mm^{-2}, t is the thickness of the test piece in m, A is the cross-sectional area in m^2, μ is the absolute dynamic viscosity of the test fluid in N sec m^{-2}, Q is the volumetric flow rate of the fluid in m^3 sec^{-1} and ψ_V is the viscous permeability coefficient in m^2.

Generally permeable materials are classified on the basis of the permeability coefficient. Alternatively, they are classified on the basis of a maximum or mean pore size [32]. High permeability and good solid particle retention in filters are mutually incompatible. The lower the permeability, the smaller is the minimum size of particles retained in a filter. Permeability can be decreased to specific figures by compressing the foam, but at the same time the coefficient of hydraulic resistance increases [43]. In order to produce a filter which will pass a sufficiently large volume of fluid in a given time and yet retain particles to a small size, it is often necessary to design filters with large cross-sectional areas.

3.4. Acoustical properties

Any structure that is open, and which allows sound to enter and vibrate internal strands or

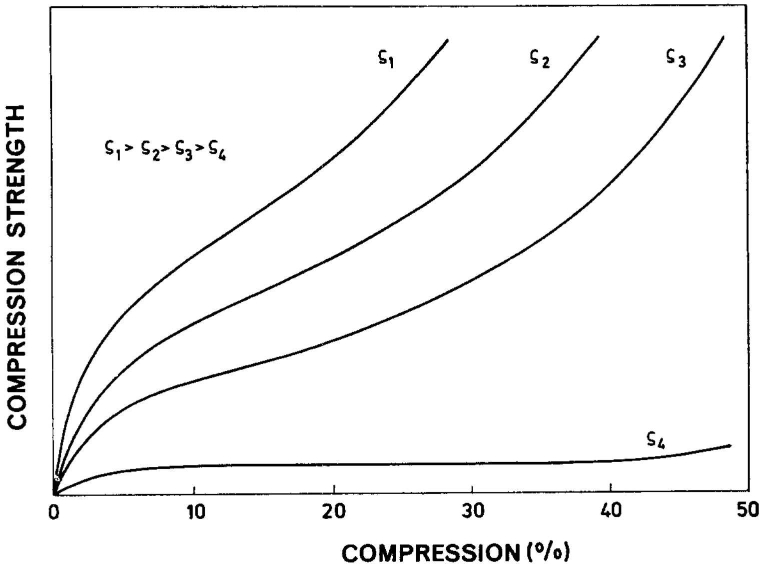

Figure 7 Compression curves of different density sponge aluminium material subjected to different static crushing forces [18].

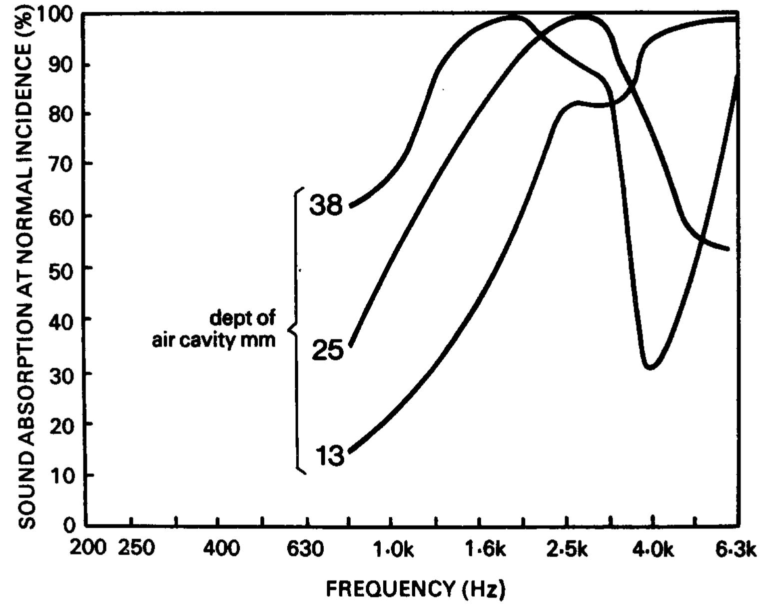

Figure 8 Effect of varying depths of air cavity behind an 80 grade compressed Retimet sample 0.94 mm thick on the sound absorption at normal incidence (air flow resistance 43.4 cgs Rayls) [45].

fibres, will absorb acoustical energy. As the sound wave enters the structure, the pressure pulse of the acoustical wave causes the strands to vibrate. The resulting mechanical movement of these strands dissipates the energy, which is released as heat [44]. A metal foam laminar absorber can give a coefficient of sound absorption as high as 99% (Fig. 8). The characteristics of pores in metallic foams affect sound absorption at different frequencies. In most cases foam performs better if many, and in some applications all of the pores are open. Pore size affects the absorption efficiency of foams at all frequencies. The smaller the pores, the greater is the absorption efficiency. From Fig. 9 it can be seen that the finest grade of Retimet, 80 grade, gives the best sound absorption [45]. Therefore, by changing the pore size and shape materials characterized by high values of sound absorption coefficient can be obtained.

3.5. Conductivities

The small amount of metal in a given volume of metal foam means that both electrical and thermal conductivities are low. For example, copper and nickel metal foams with densities of 4% have electrical conductivities which are about 1% of

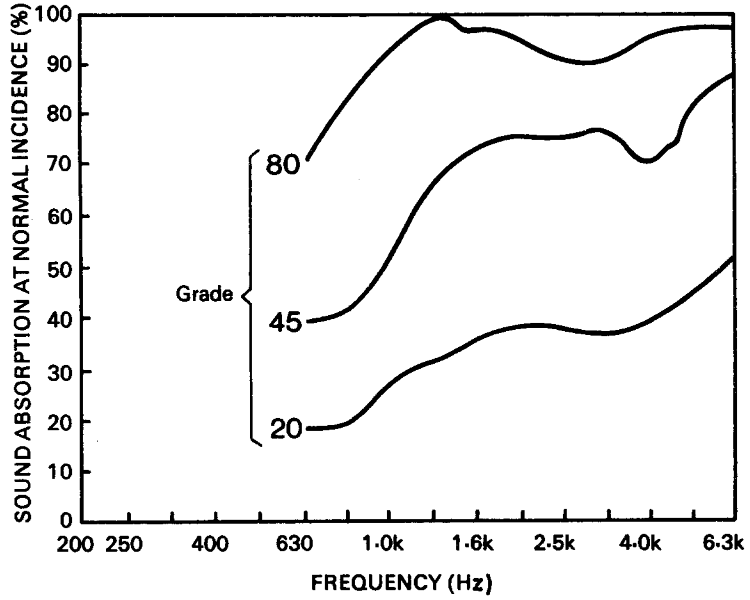

Figure 9 Effect of varying grades of 50 mm thick uncompressed Retimet on the sound absorption at normal incidence [45].

that of the parent metals. In the case of thermal conductivity, a 26 mm section of nickel Retimet grade 10 with a density of 340 kg m^{-3} (which is about 4% of the parent metal density) has a thermal conductivity of approximately 0.4 W m^{-1} K^{-1} at 400 K. This is again approximately 1% of that of the parent metal [45]. For aluminium foam of density 460 kg m^{-3} produced by the slurry technique, the thermal conductivity is 4.2 kJ (m h K)$^{-1}$ in comparison with a value of 824 kJ (m h K)$^{-1}$ for solid aluminium. The electrical resistivity of the same foam is of the order of 10^{10} ohm cm when tested at 1 kV. The break down voltage of the foam is 4 kV, when tested on a high voltage test set for an electrification time of one minute [26]. Therefore, metallic foams can be used very effectively as thermal and electrical insulating materials.

4. Applications of metallic foams

The existing applications of metallic foams cover a wide field and new uses are continually arising. It is difficult to list all the present and potential applications for metallic foams. However, it is possible to identify some so as to indicate the wide range of circumstances in which the metallic foams can be utilized.

4.1. Impact energy absorbers

Applications in impact-absorbing systems offer the greatest potential for the use of foamed metals. The possibilities range from automobile bumpers to clamping fixtures, protective envelopes for airborne equipment (crash recorders, for instance) and landing "feet" for space vehicles [1].

In many cases sponge aluminium has proved itself a good energy absorbing material. It can be used for safety pads in systems for lifting and conveying. In high-speed grinding machines by using sponge aluminium as an energy absorbing lining for the protective covers excellent results have been obtained [46]. Sponge aluminium is also suitable for forming the deformable zones of car bodies in front and behind the passenger compartment so as to improve the safety of car occupants [18].

Copper foam of 5 to 10% density has been reported to out-perform rubber for shock-absorbing mounts [34].

4.2. Filters

Porous filters are used for filtration of solid particles from streams of liquids, such as oil, gasoline, refrigerants, polymer melts, aqueous suspensions or from streams of air or other gases. The most widely used metallic filter materials are porous bronze and porous stainless steel [27]. Copper Foametal in sheet form, die cut to suit requirements, can also serve as a filter medium to prevent dirt, oxides and other foreign matter from passing along air supply lines to interfere with valves and controls. Similar material is employed for breathers in instruments, replacing wire-mesh stamped components and providing better filtration. Nickel Foametal (60% density) in special shapes is used to stop micron-size particles from contaminating hydraulic fluid, fuel oil and fluid control systems [34].

In some cases where exceptionally high resistance to corrosion is required, precious metals can be used to advantage. For example, gold foam made by metallic deposition can be used for the coarse filtration of corrosive liquids [47].

There are many similar applications such as separation media, e.g. for separating oil from water, diffusion media, the so called "spargers", for aerating liquids or for dispensing CO_2 in flowing liquids, etc. In the biochemical field compressed metal foam is used as a support for the osmotic membranes in kidney machines. The principle can also be extended to those processes relying on osmosis or reverse osmosis, such as desalination and dehydrogenation plants and in effluent treatment [45].

4.3. Silencers

The acoustic properties of metallic foam are utilized in noise prevention. For example, the operation of reducing the pressure of gas being transported over long distances by high pressure pipe lines in order to feed the gas into local networks, produce very high-intensity noise and the noise can travel along the pipe lines and reappear at long distances. Arrangements of foam metal have been designed which diffuse the gas gently, almost completely eliminating the noise, without serious interference with gas flow [45]. Metal foams have also been used in other cases of pressure reduction, such as in steam power stations and exhaust mufflers for air tools and motor cars. For example, exhaust mufflers for air tools can be made from copper sheet material (5% density) 1.5 mm thick, in the form of 50 mm by 75 mm plates, interleaved with open-mesh nylon elements to acts as spacers [34].

4.4. Flame arresters

Flame arresters are significant in preventing flame propagation along pipes and ventilating enclosures in dangerous atmospheres. Metal foam is an excellent material for this purpose because it is fire-proof and highly permeable which is consistent with flame-stopping power. In the supply of gas–air mixtures for burning, or in partly emptied petroleum and oil supply lines, a flame can occur which increases in speed as it travels. When the speed of sound is reached a violent explosion can result with pressures of 150 atm (13.8 N mm^{-2}) or more. Retimet has proved very successful in stopping hydrocarbon flames and a sample of 80 grade material only 6 mm thick has been reported to have stopped flames travelling at 210 m sec^{-1} [45].

4.5. Heaters and heat exchangers

Foamed metal is an efficient material for heaters and heat exchangers because of its high surface area. For example, nickel Foametal has been used to develop a most efficient solar collector cell, in which a strip of coated nickel Foametal retains 90% of the energy that falls on it [48]. Nickel foam is also an efficient heater–filter material for circulating air heaters. A heater–filter unit constructed of five sheets of nickel foam shows an extremely fast heating rate. For electrical resistance water heaters a nickel foam heater exhibited only one-half as much scale deposit and a slightly lower surface temperature when compared with a commercial heater [2].

4.6. Constructional materials

The distinctive structural and other physical properties of metal foams make them useful as light weight constructional materials, especially where temperatures are in excess of 200° C. Foamed aluminium has been used as core material for sandwich elements in aircraft [18]. Nickel foam has been used as wall or floor heating tiles [2]. Nickel Foametal wrapped in a cylindrical form can be used to line heat pipes, for service with various fluids including liquid metal [35]. Metal foam may also be useful as a reinforcing filling for hollow struts, where the extremely open structure will allow the passage of heating fluids for de-icing, or cooling fluids where required. A technique developed for bonding metal foam to a solid base has increased its versatility as a constructional material.

4.7. Other applications

In the chemical industry metal foam is a highly absorbent material which combines lightness and strength with chemical inertness. It can be used in fillings and plates for fractionating columns. It is also an excellent material for catalysts because of its high surface area per unit volume. Available data show that metal foam, when incorporated in a reactor, can exhibit as much as fifty times the surface area as that available in conventional materials for catalytic converters [48].

For electrochemical applications porous metal is used to produce electrodes for alkaline batteries and for fuel cells. The electrodes are generally made of nickel. For electrodes in alkaline batteries highly porous nickel with porosity of 70 to 90 vol % is used while for electrodes in fuel cells a porosity of 50 to 60% is desirable [27].

In turbine construction, metal foam is of value as an abradable seal. To allow for small variations in the dimensions of the turbine case the abradable seal can be fitted so that the turbine blades can bite into it without excessive wear. When a metal foam is used there is less material in the seal which makes it more abradable. Experiments have shown that Ni–Cr alloy foam filled with a solid lubricating composite can be successfully used in the contact seals for a rotating generator in a gas turbine engine [49].

In the field of combustion devices metal foam can be used for petrol-engine exhausts, after burners and other devices in which low-temperature combustion is required. Considerable work has already been carried out in the field of gas and liquid fuel burners. Infrared radiant gas burners made of nickel foam (5% density) can provide increased heat output per burner [34].

5. Future developments

Significant progress has been achieved in developing metallic foams. As new materials with many unique properties, metallic foams may have far reaching uses. New areas can be expected to be found in which metallic foams will constitute key elements enabling special devices or parts of unique properties to be constructed. However, foams have a lot of competitors, many of which are lower in cost. It seems important to improve the manufacturing processes in order to be able to furnish a wider variety of products of metallic foams at a lower cost. This would permit a more large-scale industrial use of these materials.

Acknowledgements

The authors would like to acknowledge the financial assistance provided by the authorities of Hunan University in support of the study leave allowed to one of them (SZ).

References

1. A. R. GARDNER, *Prod. Eng.* **38** (1967) 141.
2. L. A. COHEN, W. A. POWER and D. A. FABEL, *Mater. Eng.* **67** (1968) 44.
3. J. W. PATTEN, US Patent 4099 961 (1978).
4. A. SOSNIK, US Patent 2434 775 (1948).
5. J. C. ELLIOTT, US Patent 2751 289 (1956).
6. L. M. NIEBYLSKI, C. P. CHAREMA and T. E. LEE, US Patent 3743 353 (1974).
7. S. O. FIEDLER, J. BJORKSTEN and W. S. FIELDER, US Patent 2979 392 (1961).
8. P. W. HARDY and G. W. PEISKER, US Patent 3300 296 (1967).
9. C. B. BERRY Jr, US Patent 3671 221 (1972).
10. C. G. HALL, US Patent 3692 513 (1972).
11. L. M. NIEBLYSKI and C. P. CHAREMA, US Patent 3790 365 (1974).
12. L. G. GRAPER, US Patent 3379 517 (1968).
13. S. O. FIEDLER, J. A. BJORKSTEN and W. S. FIEDLER, US Patent 2974 034 (1961).
14. W. S. FIEDLER, US Patent 3214 265 (1965).
15. C. P. JAREMA and L. M. NIEBYLSKI, US Patent 3826 303 (1974).
16. S. E. SPEED, US Patent 3981 720 (1976).
17. H. A. KUCHEK, US Patent 3236 706 (1966).
18. W. THIELE, *Met. Mater.* **6** (1972) 349.
19. W. THIELE, German Patent 1933 321 (1971).
20. S. H. SINHA and G. N. RAO, *NML Tech. J.* **18** (1976) 21.
21. J. R. KREIGH and J. K. GIBSON, US Patent 3055 763 (1962).
22. *Jpn. Ind. Tech. Bull.* 8 (1980) 19.
23. V. E. CARTER, "Metallic Coatings for Corrosion Control" (Butterworths, London, 1977).
24. D. R. GABE, "Principles of Metal Treatment and Protection" (Pergamon Press, Oxford, 1972).
25. J. P. DROLET, *Int. J. Powder Met. Powder Tech.* **13** (1977) 222.
26. S. B. KULKARNI and P. RUMAKRISHNAM, *Int. J. Powder Met.* **9** (1973) 41.
27. F. V. LENEL, "Powder Metallurgy Principles and Applications" (Metal Powder Industries Federation, London, 1980).
28. I. M. FEDORCHENKO, *Sov. Powder Metall. Met. Ceram.* **18** 625 (1979).
29. F. C. ARRANCE, US Patent 3287 166 (1966).
30. V. A. TRACEY, *Int. J. Powder Met.* **12** (1976) 25.
31. L. BURNS and G. SCHNUCHEL, US Patent 3378635 (1968).
32. D. YARNTON, *Eng. Mater. Des.* **9** (1966) 83.
33. *Die Casting Eng.* **11** (1967) 34.
34. D. C. DILLEY, *Mach. Prod. Eng.* **125** (1974) 24.
35. P. H. THORNTON and C. L. MAGEE, *Metall. Trans.* **6A** (1975) 1253.
36. C. B. BERRY Jr. and R. J. FANNING, US Patent 3705 030 (1972).
37. C. B. BERRY Jr., US Patent 3669654 (1972).
38. C. B. BERRY Jr. and A. R. VALDO, US Patent 3725 037 (1973).
39. L. M. NIEBYLSKI, C. P. JAREMA and P. A. IMMETHUN, US Patent 3794 481 (1974).
40. J. BJORKSTEN and E. J. ROCK, US Patent 3794 481 (1972).
41. L. M. NIEBYLSKI, C. P. JAREMA and T. E. LEE, US Patent 3940 262 (1976).
42. L. M. NIEBYLSKI, US Patent 3834 881 (1974).
43. G. P. PAVLIKHIM, A. N. NIKOLAEV, S. K. BALENTSEV and V. A. KHRENOV, *Sov. Powder Metall. Met. Ceram.* **19** (1980) 511.
44. J. PIZZIRUSSO, *Mach. Des.* **53** (1981) 135.
45. H. BRAY, *Eng. Mater. Des.* **16** (1972) 19.
46. H. J. KUZIK, *Oberflache* **11** (1970) 452.
47. *Gold Bull.* **6** (1973) 7.
48. G. A. WEIMER, *Iron Age* **218** (1976) 33.
49. I. AMATO, P. G. CAPPELLI and P. C. MARTINENCO, *Wear* **34** (1975) 65.

Received 22 December 1982
and accepted 19 January 1983