Journal of Korean Powder Metallurgy Institute
Vol. 10, No. 6, 2003

P M 리 뷰

Powder Metallurgy for Light Weight and Ultra-Light Weight Materials

B. Kieback, G. Stephani, T. Weißgärber, T. Schubert, U.Waag, A. Böhm,
O. Andersen, H. Göhler and M. Reinfried

Fraunhofer-Institute Manufacturing and Advanced Materials, Winterbergstraße 28, D-1277 Dresden, Germany

(Received 5 November 2003 ; Accepted form 10 November 2003)

1. Introduction

The need for light weight materials increased in recent years mainly due to the tendency in automotive industry to reduce the weight of a car as a contribution to fuel economy. From the point of view of materials development, the requirements can be met generally by creating stronger materials, by substitution with materials of lower specific weight or by changing design principles. Powder metallurgy of light weight materials[1,2] and of ultra-light weight materials with high porosity therefore becomes interesting for future automotive applications. The possibility of creating net shape parts not needing further machining offers cost effective solutions. The requirements from the applications discussed however are high, since all standards of properties and reliability have to be met or even improved. In the present paper some new developments of PM-light weight materials and structures are discussed including aluminium and titanium alloys as well as high porous cellular structures made by powder techniques.

2. PM Aluminium Parts

P/M aluminium alloys have the potential for application in automotive components, particularly for sliding and friction parts (Fig. 1). Applications in pulleys, rod guides, shock absorber piston, oil and transmission gears are also discussed. Apart from wear and strength problems which are still an issue, these components require extremely tight control of dimensions[3,4]. Forged P/M aluminium connecting rods are of interest since they offer the potential to reduce moving masses in the engine[5]. The important properties are fatigue strength, tailored thermal expansion and low cost (minimum value for the room temperature fatigue strength of about 200 MPa, CTE < 17 ppm/K). Properties of importance are also modulus, ductility and creep resistance. Significant previous efforts have been made in this area[6]. Among the pioneers who significantly contributed to this subject, Hitachi Powdered Metals Co., Ltd. has developed an P/M aluminium connecting rod from an AlSiCuMgNi alloy for non-automotive applications, e.g. in compressors[7]. Sumitomo Electric Industries, Ltd. has also reported the development of a material that has been evaluated for a connecting rod using aluminium matrix composites reinforced with SiC particles reaction-sintered in a nitrogen atmosphere to a near-net shape[8].

To produce cost effective parts atomised aluminium

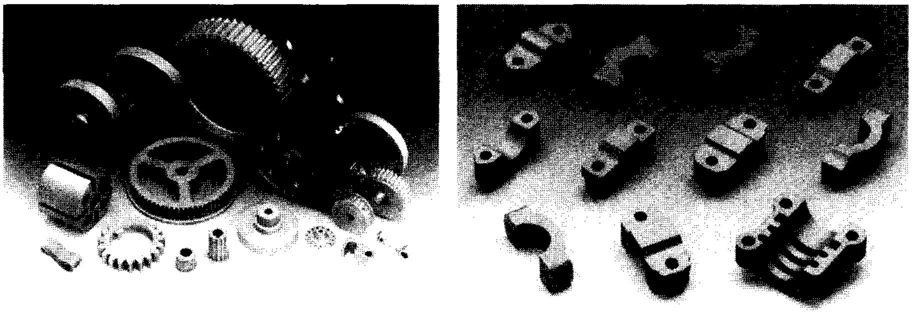

Fig. 1. Examples of P/M aluminium structural components (left) and cam caps by GKN (right).

powder is mixed with elemental or master alloy powders to make up the desired final alloy composition. Compared to Fe powder, the Al powders show a lower apparent density but better compressibility. An important role of the compaction step for aluminium powders is to break-up the surface oxides and to create metal-to-metal bonds. The lubricant added must be burned out before the sintering temperatures between 550°C and 630°C are reached. The dimensional changes during sintering and the resulting mechanical properties are strongly dependent not only on the temperature but also on atmosphere purity - clean and dry N_2 with dew point better than –40°C being commonly used - and on careful delubrication[9)].

Recent work was concentrated on improving the design of the alloys. Most of the structural P/M aluminium alloys used today are based on wrought or cast alloy compositions; most are based on the 2000 and 6000 alloys and contain Cu, Mg and/or Si. More recently, also considerable work has been invested into AlZnMgCu sintered alloys[10,11)]; noticeable activities have been reported especially in the 1990s[12,13)]. An area of great interest is the development of AlSi alloy products. P/M processing offers significant advantages in its ability to produce hypereutectic alloys with relatively fine Si particles, which can provide a wear-resistant and machinable product. Approaches involving blending of high and low Si powders as well as additions of sintering aids are under investigation[14)]. In addition, a mix of plain aluminium powder and a masteralloy containing all alloying elements has been developed by Ecka for this type of sintered alloys[15)]. The Si content of these AlSi-based alloys may vary from 14 to 35% by e.g. changing the ratio Al-masteralloy.

In Fig. 2, a typical shrinkage curve of powder compacts of an AlSi-based powder blend and some corresponding optical micrographs are shown. The green compacts have about 93% total density (TD) and a heterogeneous microstructure. The swelling effect at about 520°C is explained by supersolidus liquid phase formation from the masteralloy. The liquid phase activates the desification process after an incubation time of about 30 minutes to about 99,8% TD during sintering for 60 minutes at 550–560°C. Simultaneously Si grain sizes increase to 7 8 μm.

The mechanical properties of the alloy AlSi14Cu2,5Mg0,6 (Alumix 231) are given in Table 1. Attractive strength and hardness levels have been attained by age hardening.

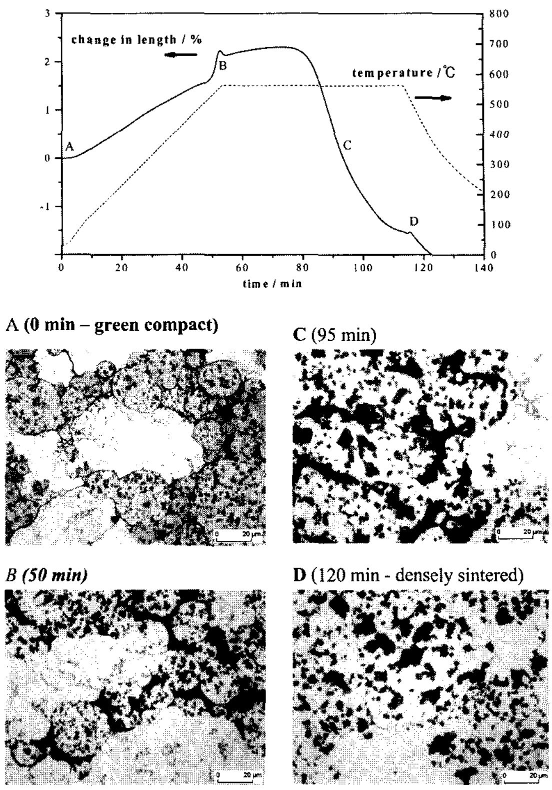

Fig. 2. Shrinkage of AlSi-based powder blend and optical micrographs showing the microstructural evolution during sintering.

Table 1. Mechanical properties of sintered Alumix 231 (17).

Hardness T1/T6	HB2,5	105/130
Yield strength at RT T1/T6	MPa	210/300
Tensile strength at RT T1/T6	MPa	230/340
Elongation at RT T1	%	1,4
Yield strength at 250°C	MPa	190
Tensile strength at 250°C	MPa	200

The main phase that determines the value of the coefficient of thermal linear expansion (CTE) of the alloys is silicon. Fig. 3 illustrates the decrease of CTE if the Si level in the alloys increases. This capability to change physical properties is important in applications where CTE matching is critical in part design (e.g. conrods).

The silicon content is essential for good wear properties because these particles control the direct contact between the matrices. Details of wear tests are given in[16)].

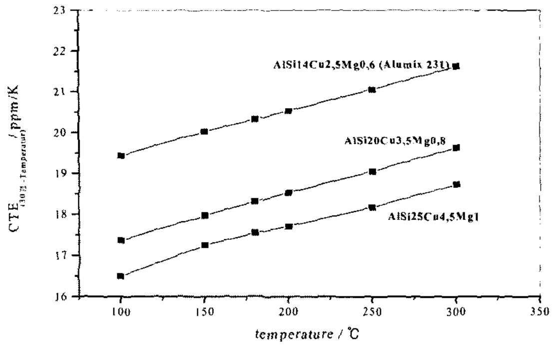

Fig. 3. Coefficient of thermal expansion vs. temperature for different sintered AlSi alloys.

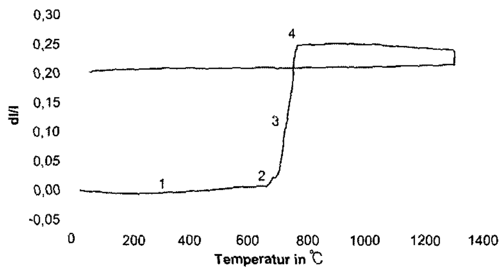

Fig. 4. Dilatometer plot of a Ti-Al sample with 50 at.% Al (vacuum, 10 K/min).

3. Titanium Alloys

The market of PM titanium and titanium alloys at present does not exceed 50 t/Y. The main reason is the high price of metal powders partially coming from the raw materials extraction. Several attempts to reduce the costs of the starting materials are studied and future development of high strength PM titanium parts at competitive costs can be expected. One of the interesting areas of application are materials based on TiAl intermetallic compounds.

Reaction sintering is an interesting way for the preparation of intermetallic materials. However it was shown that a severe swelling of the green samples during the sintering process prevents a full and homogeneous densification of the materials[17-19].

The dilatometric curve (Fig 4) for samples made with spherical Al and Ti powders (grain size Ti: <315 μm, Al: <160 μm) mixed in a composition of 50/50 at.% Al/Ti and compacted at pressures up to 800 MPa (90% density) demonstrates the swelling effect. Details of the processes causing the density decrease are given in[20-22].

It was shown that the problems considering densification of the green compacts and level of impurities of the final product can be solved using a high energy milling technique. Milling was carried out without additives to decrease the level of impurities namely oxygen and carbon. An Al7.6Ti-prealloy was used to improve milling behaviour due to its lower ductility.

Oxygen and carbon contents of below 1000 ppm were achieved using this technique. Furthermore this technique guarantees a fine microstructure with grain sizes as small as 10 μm and below.

Further work has to be done for alloy development and technology optimisation. The route described has however a great potential to produce complex shaped parts like exhaust valves with low cost starting materials and using established PM processes. It is interesting to mention, that the powder processing method was also successfully applied to other systems, e.g. silicides, Ni- and Fe- aluminides. Further reduction in the costs of Ti-metal powder would assist future developments.

4. High Porous Cellular Metal Structures

Highly porous metals have a combination of interesting properties: controlled low density, high specific stiffness, high energy absorption per unit mass, thermal and acoustical insulation. Especially the automotive industry is showing a strong interest on this light weight materials. Open cell structures have been used in different applications such as for heat exchangers, filters or batteries. Closed cell structures are suitable for applications such as for light weight structures (high specific stiffness), energy absorption, vibration damping and thermal insulation.

Reviews of manufacturing processes and characterization of highly porous metals are given in[23-25]. One of the most studied routes towards cellular metals of the last decade was the Al-foam produced by foaming liquid aluminium by TiH_2 decomposition.

Another way is to use "building blocks" (pores surrounded by the material) and to build up the needed structure cell by cell. Since the basic elements are in general spherical, these structures are called "hollow sphere structures". To use metal powders was first proposed in[26]. An intensive R&D programm since 1998 led to a significant progress in this technology[27-33].

Fig. 8 shows the main processing steps for the MHS manufacturing: foamed polystyrene (EPS), is used as a

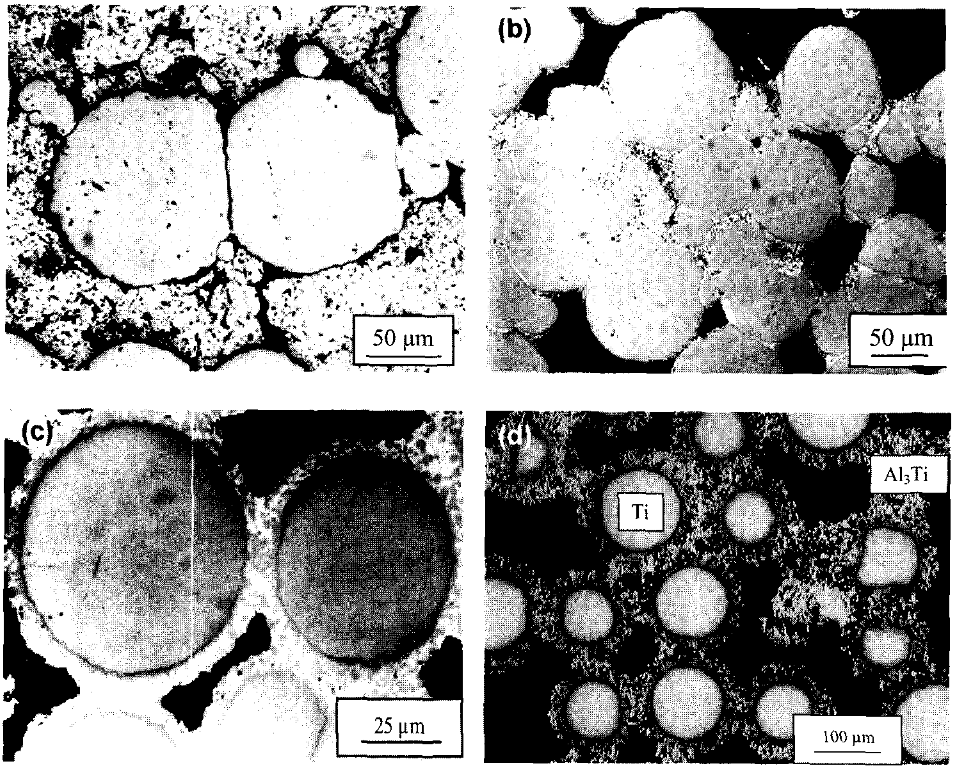

Fig. 5. Microstructure evolution in a Ti-50 at-%Al compact during sintering: (a) T < 660°C, (b) 665°C, 0 min, (c) 665°C, 2 min and (d) 750°C, 15 min.

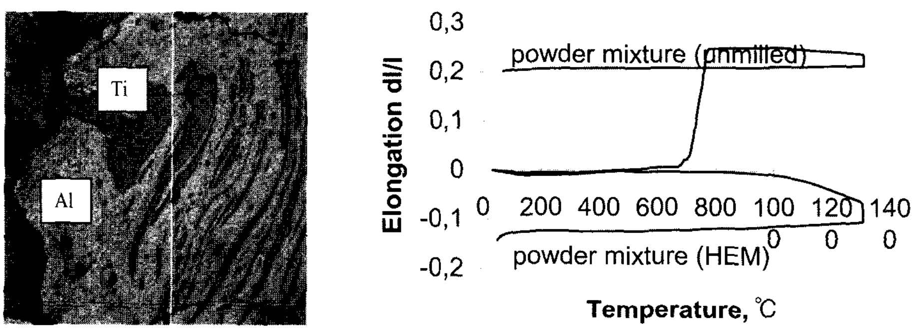

Fig. 6. Microstructure of a high energy milled Ti-Al-Powder and dilatometer curve of the milled powders compared with a powder mixture.

spherical cell forming substrate. In a fluidized bed coating equipment, these foamed EPS-spheres are held in continuous movement by a stream of hot gas. With a nozzle system, a metal powder-binder-suspension is atomized coating the styrofoam spheres. Both the binder used to fix the powder particles and the styrofoam cores are removed in the following thermal treatment. At higher temperatures, the metal powder is sintered to a dense shell wall. A wide range of powder materials can be used for this processing route.

The diameter distribution of the sintered spheres depends directly from the diameter distribution of the substrate material and the reproducible shrinkage during the sintering. Therefore the advantage of hollow sphere structures is the uniform cell size what makes the properties predictable. Hollow spheres can be manufactured in a diameter range of approx. 0.5 mm to 10 mm with wall thicknesses of 20 µm to 1000 µm.

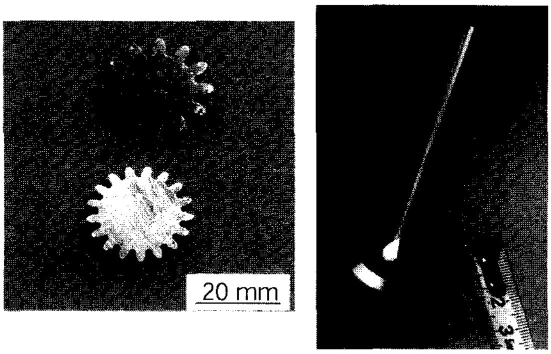

Fig. 7. Parts produced by High energy milling of Ti-Al-alloy mixtures and pressurless sintering at 1300°C followed by HIP without capsule.

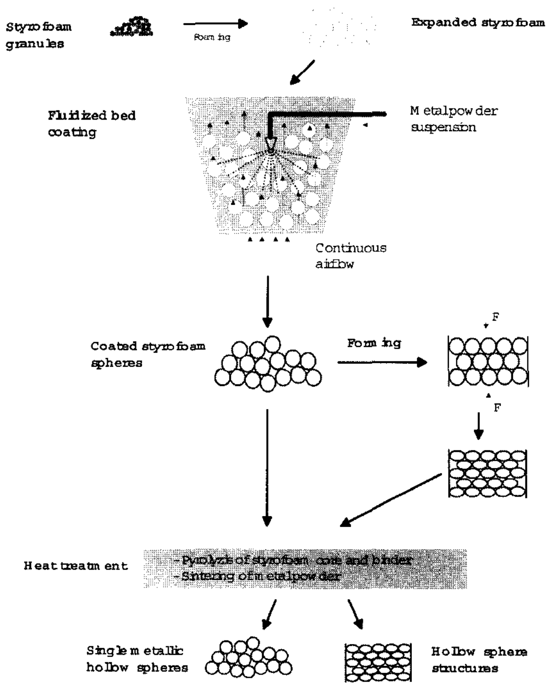

Fig. 8. Processing of metallic hollow spheres (MHS) and MHS-structures.

The density of structures built up by resin bonding, soldering or sintering together the individual spheres (see Fig. 8) depend mainly on the wall thickness/sphere radius ratio (Fig. 9).

The structure in final body may be modified by a deformation in a die of the sphere arrangements in the green state. The elastic styrofoam core prevents the damage of individual spheres and the contact area between spheres increases. The form is easily fixed by a slight temperature increase. As an example stainless steel hollow sphere structures were debinded at 600°C and sintered at 1120°C for 60 min in H_2. The results for different lots are given in Table 2. A typical microstructure and a deformation curve of a hollow sphere structure is shown in Fig. 10. The structure is characterised by closed cells with some open space between the former spheres. The compression test shows the isotropy of properties in three dimensions.

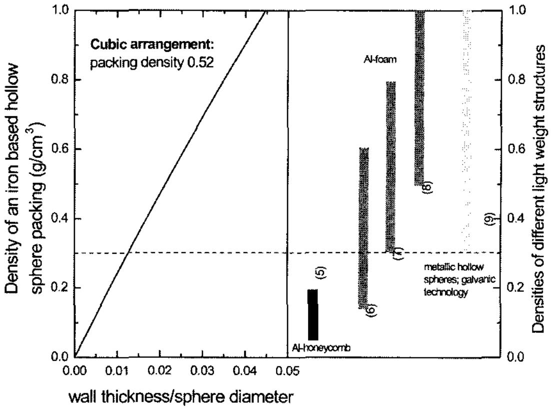

Fig. 9. Dependence of the density of steel hollow sphere structures from the wall thickness/sphere diameter ratio.

Table 2. Properties of sintered hollow sphere structures (steel)

Steel sample	Sphere diameter (μm)			Structure density (g/cm³)	Cell wall porosity (%)
	d_{05}	d_{50}	d_{95}		
A	1730	1890	2100	0.64	8
B	1520	1740	1890	1.18	4
C	2420	2650	2840	0.77	19
D	2360	2620	2840	1.45	8

For sound absorption tests samples were prepared from different sphere sizes with structure densities between 0,4 to 0,64 g/cm³ and sphere diameters between 1 and 7 mm (see Fig. 11).

The results of the sound absorption test are quite promising, since better absorption was measured compared to widely used "Advantex" glass wool[33].

The hollow sphere method may be used with a great variety of metals and alloys if powders are available in the necessary fine particle sizes. Many systems already have been tested: iron, carbon steels, Fe-Cu-alloys, stainless steel, Fe-Cr-Al- alloys, superalloys, tungsten, molybdenum, gold, silver and the technique is also tested with ceramics. Up to now there are no final estimates about the cost. One important cost fac-

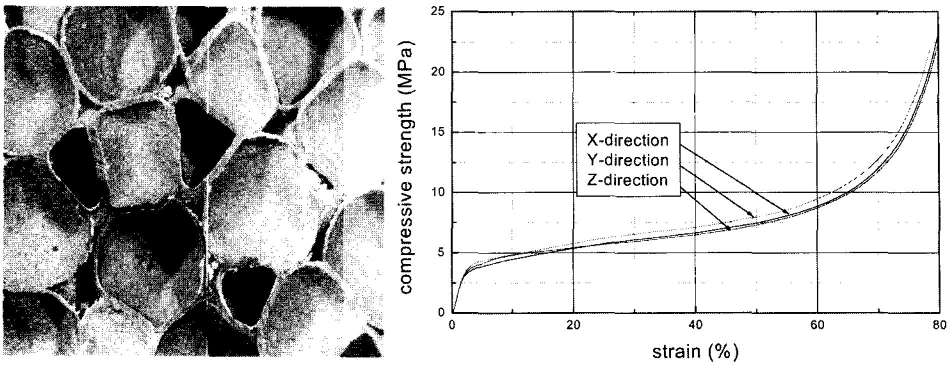

Fig. 10. Typical microstructure of a sintered hollow sphere structure and deformation curves of a structure with a density of 0,65 g/cm³.

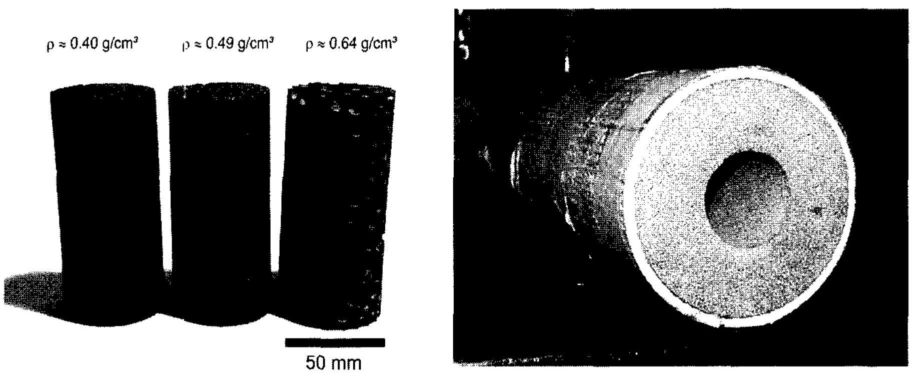

Fig. 11. Samples for sound absorption tests (diameter: 1, 2,5 and 7 mm).

tor comes from the powder. The Styrofoam, the coating operation and the sintering process are considered to be of less importance for the final costs since low cost material and mass production techniques are used.

Further improvements are expected from structures using the same route as described earlier but with an additional step after forming the structure from green spheres. If the cell walls are modified to show highly elastic or viscous behaviour a secondary expansion of the Styrofoam balls closes the space between the spheres and an ideal cell structure is formed (Fig. 12).

5. Summary

As in other areas of materials technology, the tendency towards light weight constructions becomes more and more important also for powder metallurgy.

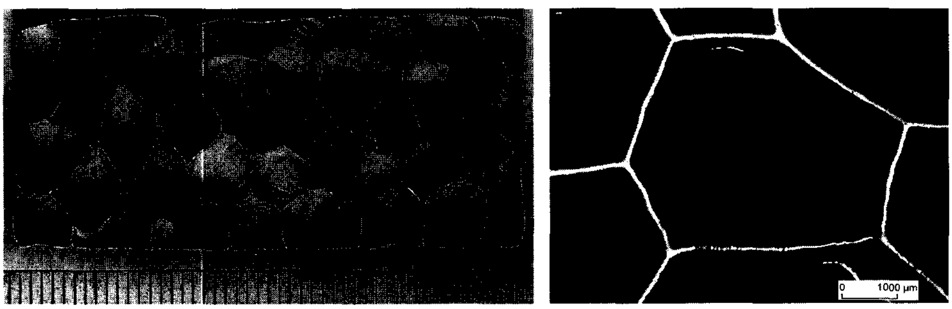

Fig. 12. Regular cell structures formed from green metal hollow spheres by additional expansion of the Styrofoam core.

The development is mainly driven by the automotive industry looking for mass reduction of vehicles as a major factor for fuel economy. Powder metallurgy has to offer a number of interesting areas including the development of sintered materials of light metals. PM aluminium alloys with improved properties are on the way to replace ferrous parts. For high temperature applications in the engine, titanium aluminide based materials offer a great potential, e.g. for exhaust valves. The PM route using elemental powders and reactions sintering is considered to be a cost effective way for net shape parts production. Furthermore it is expected that lower costs for titanium raw materials coming from metallurgical activities will offer new chances for sintered parts with titanium alloys. The field of cellular metals expands with the hollow sphere technique, that can provide materials of many metals and alloys with a great flexibility in structure modifications. These structures are expected to be used in improving the safety (crash absoption) and noise reduction in cars in the near future and offer great potential for many other applications.

References

1. H. Hunt : Metal Powder Report May (2000) 28.
2. Ch. Lall, W. Heath : Int. J. Powder Metall. **36** (2000) 6, 45.
3. R. Shivanath *et al.* : Proc. of the Int. Powder Metallurgy Aluminium & Light alloys for Automotive Applications Conference, Michigan, MPIF (2000) 105.
4. K. Dollmeier, B. Hofmann and P. Bishop : Proc. of Euro PM2000 (2000) 93.
5. M. Weber : Pulvermetallurgie in Wissenschaft und Praxis **7** (1991) 119
6. J. E. Allison *et al.* : Proc. of ICCM-10, Whistler, B.C., Canada (1995) II-345
7. Z. Ishijima *et al.* : Adv. Powder Metall. & Partic. Mater. (1996) 14.3.
8. Y. Takeda and T. Hayashi : Adv. Powder Metall. & Partic. Mater. (1996) 10.41.
9. H. C. Neubing, G. Jangg : Metal Powder Report **42** (1987) 354.
10. F. J. Esper, G. Leuze : Proc. 4th Europ. PM Symp. Grenoble **3** (1975) 8-2-1.
11. M. Mühlburger and P. Paschen : Z. Metallkunde **84** (1993) 346.
12. G. B. Schaffer and S. Huo : Adv. Powder Metall. & Partic. Mater. **4** (1996) 14.
13. H. Danninger and H. C. Neubing, J. Gradl: Proc. PM`98 Granada, EPMA **5** (1998) 272.
14. L. H. Low : Proc. of the 2. Int. Powder Metallurgy Aluminium & Light Alloys for Automotive Applications Conference, Michigan, MPIF (2000) 123.
15. H. C. Neubing, J. Gradl and H. Danninger : Int. Conf. of Powder Metallurgy and Particulate Materials, PM2-Tec02, Orlando, MPIF (2002).
16. T. Schubert, H. Balzer, H. C. Neubing and H. Gans : Proc. Int. Congress on Advanced Materials and Processes, Materials Week, 30.09.-02.10.2002, München
17. A. Böhm and B. Kieback : Z. Metallk., **89**(2) (1998) S. 90.
18. A. P. Savitskii : Liquid Phase Sintering of Systems with Interacting Components Russian Academy of Sciences, Tomsk, 1993.
19. M. Dahms, G. Leitner, W. Poeßnecker, S. Schultrich and F. Schmelzer : Z. Metallkd., **84**(5) (1993) S.351.
20. A. Böhm and B. Kieback : Z. Metallk., **89**(2) (1998) S. 90.
21. A. Böhm : Dissertation, TU Dresden; 2000.
22. A. Böhm, R. Scholl and B. Kieback : Proc. 15th International Plansee-Seminar, Vol. 1, 626-635.
23. J. Banhart and H. Eifert (Eds.): Metal Foams Fraunhofer USA Metal Foam Symposium, Stanton, Delaware, USA, Oct. 7-8, 1998.
24. G. Stephani and O. Andersen: 2001. Solid state and deposition methods. In Handbook of Cellular Metals, ed. P. Degischer, B. Kriszt, VCH Wiley 2001.
25. T. D. Claar, C. J. Yu, D. Kupp and H. Eifert : Proc. PM^2Tec 2000, New York, USA, p.12-71, 2000.
26. M. Jaeckel and H. Smigilski : German Patent 3 **724** (1987) 156.
27. U. Waag, L. Schneider, P. Loethman, G. Stephani and B. Kieback : Proc. of PM2000 World Congress, Kyoto, Japan, p.379, 2000.
28. L. Schneider, U. Waag and P. Loethman : Proc. of PM2000 World Congress, Kyoto, Japan, p.510, 2000.
29. U. Waag, L. Schneider, P. Löthman and G. Stephani : Metal Powder Report, **1** (2000) 55, 29-33
30. G. Stephani, U. Waag, P. Löthman, O. Andersen, L. Schneider, F. Bretschneider and H. Schneidereit : Proc. PM2TEC Conference (APMI), 30.05. 03.06.2000, New York, USA.
31. P. A. Löthman, O. Andersen, J. Gründer and G. Landgraf : Proc. of Materials Week, Munich, 25-28 September 2000.
32. J. Gründer, G. Landgraf, O. Andersen and P. Löthmann : in J. Banhart, M.F. Ashby, N.A. Fleck (Eds.): Cellular Metals and Metal Foaming Technology, Bremen: MIT Publ. 397-402, 2001.
33. U. Waag, G. Stephani, F. Bretschneider and H. Venghaus: Proc. Int. Conf. of Powder Metallurgy and Particulate Materials, PM2Tec02, Orlando, MPIF (2002).