Novel Techniques for the Fabrication of Titanium Aluminide Thermal Protection Systems (TPS) for Aerospace Applications

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Abstract

There is significant interest in the use of intermetallic alloys, such as titanium aluminide, in Thermal Protection Systems (TPS) on next-generation low orbit and re-entry space vehicles, based on their good mechanical performance at elevated temperatures, resistance to oxidation and low specific density. However, actual applications of titanium aluminides have been limited due to their low ductility at ambient temperature and difficulty in shaping the alloys using traditional metalworking practices such as machining, cold working, casting, etc. Ultra-lightweight, porous titanium aluminide alloys are being fabricated based on technologies being developed at the Fraunhofer Institute and Fraunhofer USA Centers for Manufacturing and Advanced Materials, located in Dresden, Germany and Newark, DE, USA, respectively. Powder metallurgy processing routes are being utilized to fabricate hollow metal spheres and reaction sintered TiAl and $TiAl_3$ intermetallics. The processing, microstructures, and selected properties of these controlled-porosity materials are presented, along with a discussion of potential application as thermal protection systems.

Introduction

Cellular structures based on metals, ceramics or polymers are being used with increasing frequency as a means of reducing weight in aerospace, naval and land-based applications, for such novel components as energy absorbing media in personnel armor, aircraft structures, vehicular blast panels, vibration damping structures, and as biomedical implant materials designed to replicate natural bone tissue structure. By tailoring pore structure (size, shape and volume fraction) performance of these materials can be engineered to meet the requirements of each application. In aerospace applications, for example, lightweight components with a high specific stiffness (stiffness to weight ratio) are desirable. The industry workhorse -honeycomb structures - suffer from relatively high cost, adhesive bonding delamination, anisotropic properties and lack of heat resistance. To meet new and demanding requirements, a wide range of alternative cellular metal structures have been developed and tested extensively. Cellular components can be produced by various means, including metal casting, powder metallurgy, electro-deposition, and chemical and physical vapor deposition [1,2].

Hollow sphere structures

Due to the availability of structures in a wide range of compositions and highly controllable pore characteristics, the fabrication of hollow metal spheres via a P/M process is one increasingly important technology for fabricating cellular metal components. Hollow metal spheres are manufactured by coating expanded polystyrene (EPS) spheres with a metal powder suspension as the spheres move turbulently through a fluidized bed. This movement provides a uniform coating on the EPS spheres and allows almost instant drying of the slurry liquid. The coated spheres are then heated to pyrolyze the binder and EPS, followed by sintering of the metal powder particles to form a dense shell [3]. Other substrate materials can be used, but EPS has the advantage of being low cost and very low density with clean pyrolysis. A schematic of the process to produce hollow metal spheres is shown in Figure 1 [3].

The hollow sphere technology has been used to produce metallic structures in Ti, Ti-6Al-4V and TiAl as well as Fe, Ni, 316L stainless steel, Inconel 718 and other materials. Several examples of spheres and test components in Ti-based alloys and other compositions are shown in Figure 2.

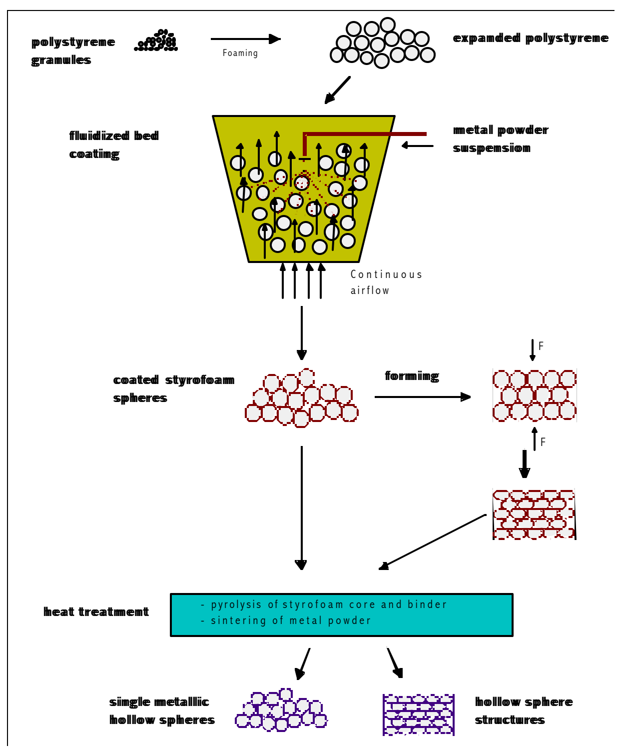

Figure 1. Schematic view of the process to produce hollow metal spheres.

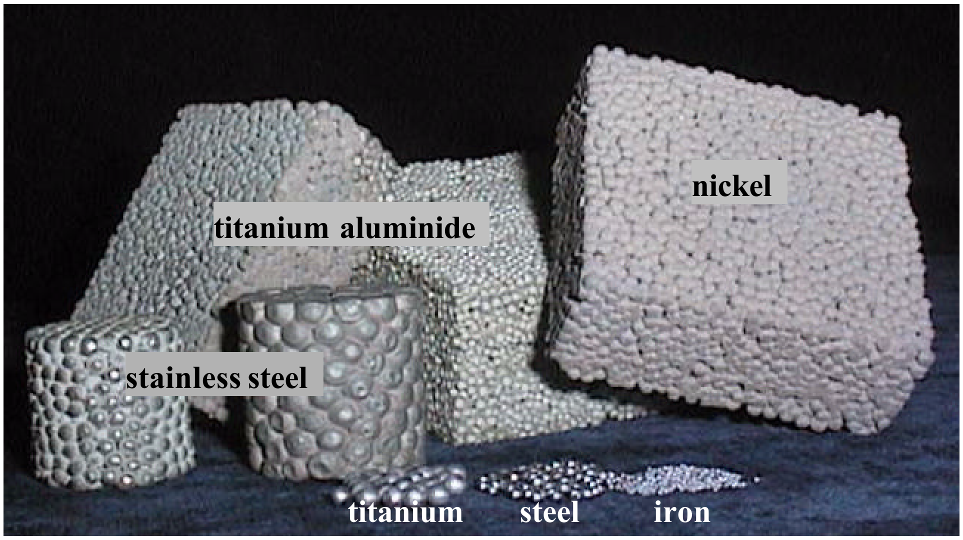

Figure 2. Examples of hollow sphere structures in various compositions.

In recent work, highly porous titanium aluminide structures were successfully fabricated and evaluated for use as aerospace thermal protection components. Spheres produced from titanium aluminide pre-alloyed powders (Crucible Research, Pittsburgh, PA, USA and shown in Figures 3 and 4) were sinter bonded into 50 mm x 50 mm x 25 mm thick plates. Sintered bulk porosities of >90 volume % were routinely reached using 2 mm diameter spheres with wall thicknesses ~60-80 µm. By increasing the sphere diameter to ~ 3mm, thereby increasing the diameter to wall thickness ratio, bulk densities >95 volume % were ultimately achieved. A close-up of one of these structures is shown in Figure 5.

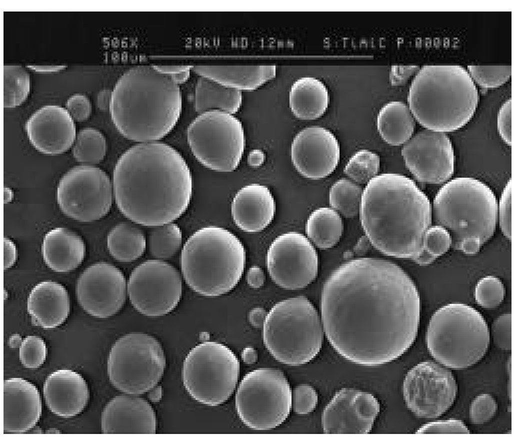

Figure 3. Pre-alloyed titanium aluminide powder from Crucible Research (506X)

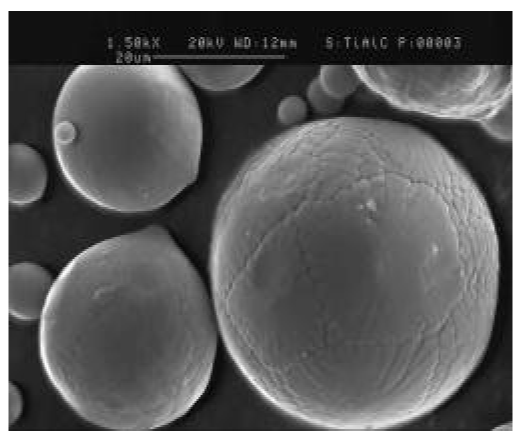

Figure 4. Pre-alloyed titanium aluminide powder from Crucible Research (1500X).

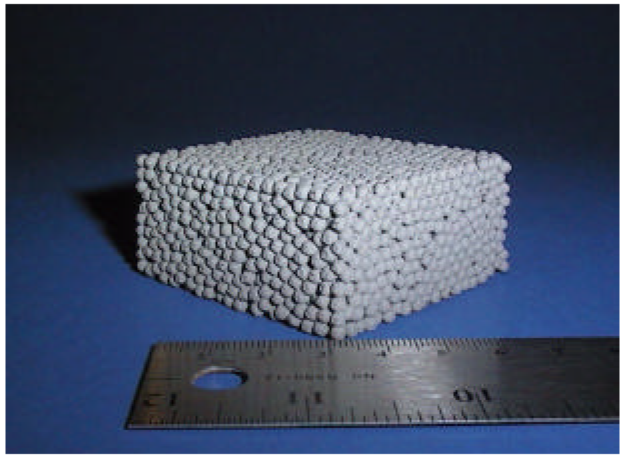

Figure 5. Sintered titanium aluminide hollow sphere structure, fabricated from 3 mm diameter spheres.

Reactive Sintering of Porous Titanium Aluminide

An alternative approach to fabricating porous titanium aluminide structures has also been investigated, relying on the well documented macrostructural swelling that takes place during pressureless reactive sintering of Ti + Al and other intermetallic powder mixtures. During production of dense titanium aluminide alloys, this swelling behavior prevents full and homogeneous densification during reactive sintering, but can be used to generate desirable porosity in sintered Ti+Al components. An increase in porosity is achieved by redistribution and penetration of molten Al into Ti-Ti contacts causing a displacement of Ti particle centers AND the formation of a highly porous $TiAl_3$ layer. This process is shown schematically in Figure 6 [4].

A direct method for the fabrication of porous Ti-Al components was evaluated, using reactive sintering of die-pressed compacts of elemental Ti and Al powder. This approach relies on the high-temperature reaction mechanisms previously described to develop a porous microstructure throughout the die-pressed component. By pre-blending relatively fine Ti and Al powders, then pressing to the maximum achievable green density, a homogeneous microstructure is produced which supported the development of porosity during reactive sintering. The Al powder (-75 μm) was provided by Eckart America L.P. (Louisville, KY, USA), and Ti powder (-45 μm) was provided by Pyrogenesis Inc. (Montreal, Quebec, Canada) as shown in Figures 7 and 8 respectively.

Stage I -

Solid state sintering from RT to 660 ^{o}C (melting point of Al)

Stage II -

Al melt formation and melt rearrangement

Stage III -

Formation of $TiAl_3$, penetration of Al melt into $TiAl_3$ grain boundaries and $TiAl_3$ disintegration

Stage IV –

Formation of highly porous $TiAl_3$ layer on the Ti surface

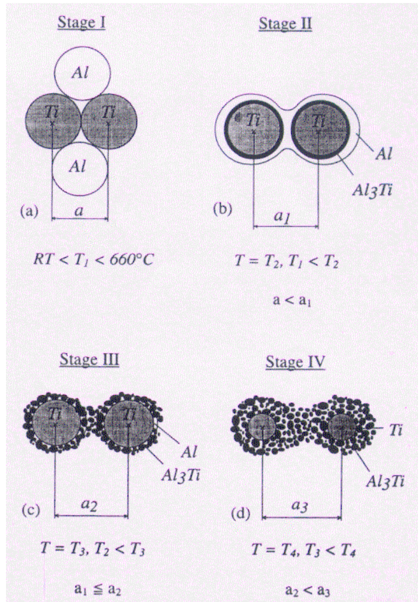

Figure 6. Schematic representation of phase formation and macroscopic swelling behavior during reactive sintering of Ti-Al.

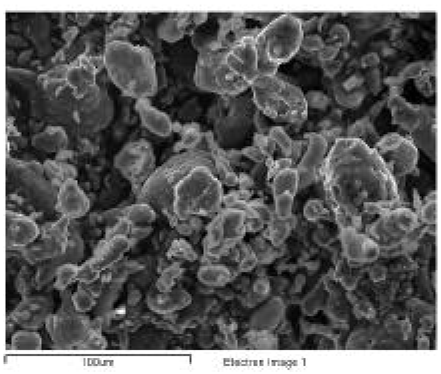

Figure 7. Al powder (-75μm) from Eckart America, L.P. used in the production of reactively sintered Ti-Al components.

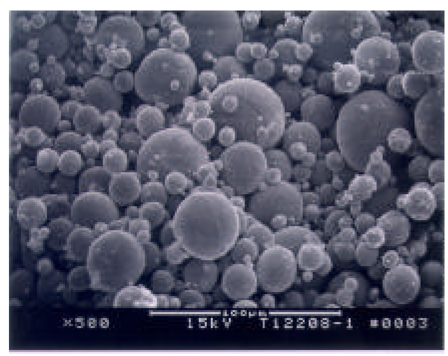

Figure 8. Ti powder (-45 μm) from Pyrogenesis Inc. used in the production of reactively sintered Ti-Al components.

Using a 50 atomic % mixture of each material without binder or lubricants, Ti and Al powders were pressed at 138 MPa (20 kpsi) into ~50 mm square billets, approximately 12 mm thick, then heat treated at 1300°C in a flowing Ar atmosphere. Green densities after pressing averaged about 71% of theoretical density. Samples of the die compacted, reactively sintered titanium aluminide components are shown in Figure 9.

Figure 10 shows a typical microstructure of the die compacted Ti-Al components displaying the porosity resulting from low-pressure compaction and reactive sintering. Linear expansion in the pressing direction averaged about 15%, and about 12% perpendicular to the pressing direction. The bulk porosity increased from ~29 volume % in the "as-pressed" state to ~ 54 volume % after reactive sintering. X-ray diffraction performed on a representative section of the sintered components shows a mixture of TiAl, $TiAl_2$, $TiAl_3$ and Ti_3Al in addition to minor mixed oxide phases. Free Al was detected, but no pure Ti was observed via XRD. Further analysis of the samples was not carried out, nor were any other attempts made to optimize the structure or composition of the component.

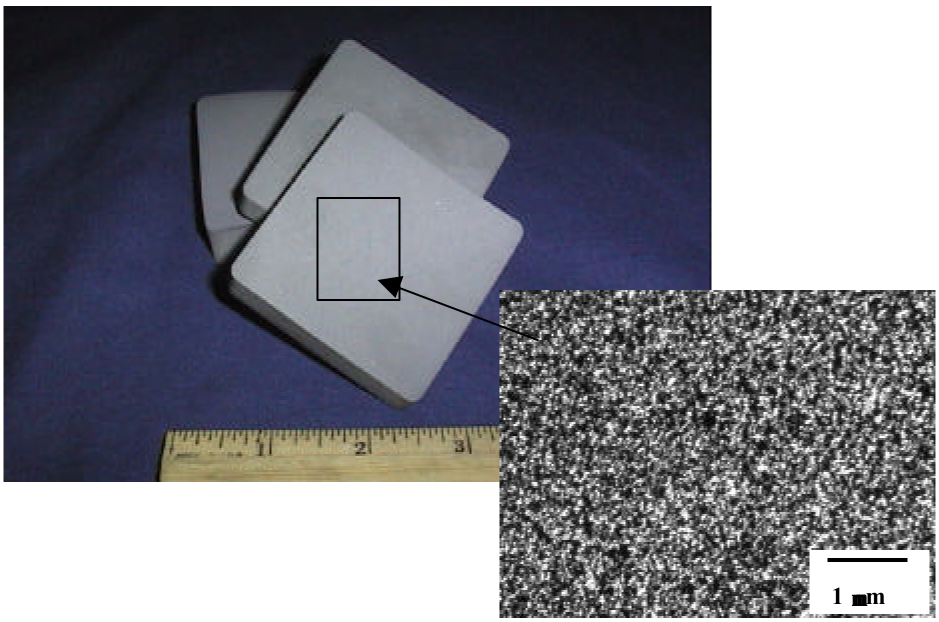

Figure 9. Reaction sintered Ti-Al plates with a close-up of the as-sintered surface (inset).

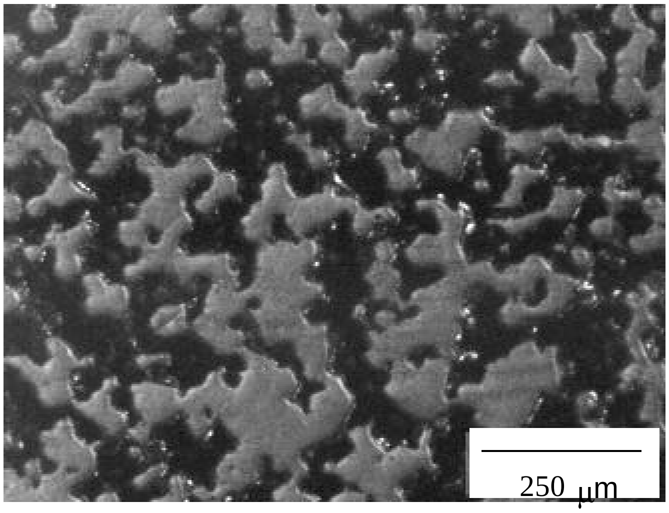

Figure 10. Polished cross-section of reactively sintered Ti-Al specimen (porosity ~ 54 volume %).

Acknowledgment

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