Project title: Lightweight Aluminum/Nano composites for Automotive Drive Train Applications:
Company: IAP Research, Inc. **PI:** Bhanumathi Chelluri
DOE award # DE-FG02-06ER84540

PHASE I - FINAL REPORT

One of the goals of the DOE PNGV, DOE Freedom Car and Vehicle Technologies, Freedom Car and Fuel Program, United States Automotive material Partnership (USAMP) is to reduce vehicle weight by 50 % by using lightweight materials in place of current steels. The project objective is to develop high performance, low-cost, lightweight aluminum metal matrix composite components for use in automotive drive train applications. The targeted application is to produce net-shape gears using Dynamic Magnetic Compaction.

The Phase I SBIR project has achieved several important results that we believe will impact future P/M net shape manufacturing of aluminum parts. The highlights of our Phase I project work are divided into successfully processing (1) aluminum alloy powders and (2) nanocomposite powders. During the Phase I, we have successfully demonstrated the feasibility of the following:

- Processing air atomized aluminum powders via Dynamic Magnetic Compaction (DMC) pressing and subsequent sintering to produce parts with properties similar to wrought aluminum.
- Processing aluminum powders without lubes via press and sintering to 100 % density. This will preclude a delube cycle in sintering and promote environmentally friendly P/M processing.
- Processing aluminum powders via press and sintering with minimum shrinkage for net shape fabrication. Aluminum powders processed via conventional powder metallurgy process produce too large a shrinkage. Because of this, sinter parts have to be machined into specific net shape. This results in increased scrap and cost.
- Fully sintered aluminum alloy under this Phase I project has shown good particle-to-particle bonding and mechanical properties.
- Dispersing nano silicon carbide (SiC) powders into aluminum matrix comprising micron-sized powders (<100 microns) using a proprietary process.
- Processing aluminum composites with nano SiC reinforcements using our press and sinter process.

Success of Phase II and III development work will enable significant technical capabilities in the design and manufacture of aluminum components to replacing steel power train components. Aluminum because of its high-strength and low-weight characteristics, allows automakers to maintain vehicle size while reducing vehicle weight. Thus, fuel economy is improved while cost effectively reducing vehicle exhaust emissions. Other industries -including defense- will also benefit from developing this process to manufacture low-cost Al-MMC materials.

Phase I results:

Feasibility work on Aluminum alloy powders without lube:

The Phase I project work was conducted using air atomized aluminum powders from AMPAL Inc. Specifically AMB 2712 powders with a chemical composition of (in wt. %): Cu-3.6-4; Si-0.6-0.9, Mg-0.8-1.2, and Al-Balance were used. The average particle size was 60-80 microns with irregular morphology. Figure 1 shows the microstructure of the aluminum powders. Conventionally the powders are mixed with 1.5 % lube for pressing and the lubes are burnt out during a delube cycle while sintering. Under the Phase I project, we have demonstrated that the powders can be successfully processed without any lube.

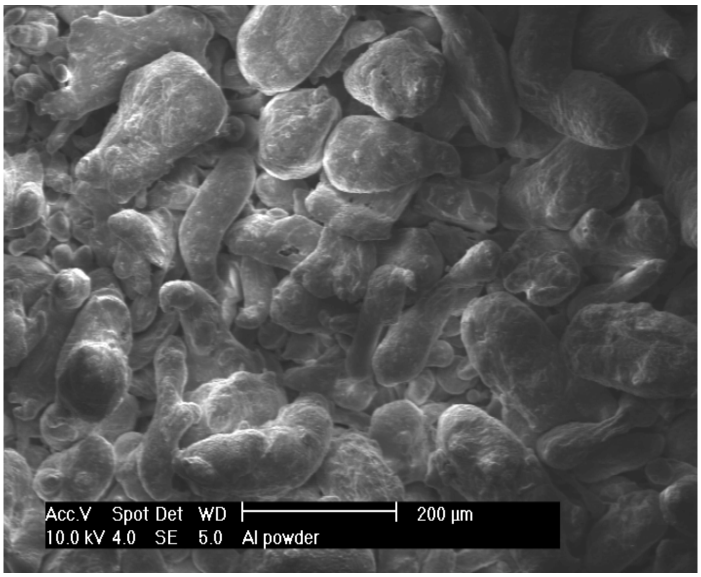


Figure 1: Scanning Electron Micrograph of 2712 air atomized aluminum powders of irregular morphology used for Phase I project

The cylindrical rods of 3.25" long and 0.75 " diameter were pressed using DMC compaction. The pressed green samples were then sintered at temperature of 1115 ºF for 30 minutes with dew point of -40 ºF under a nitrogen atmosphere. The density of green and sintered samples was measured using Archimedes' principle according to ASTM standard. At optimum sintering conditions, twenty samples were pressed and sintered from powders with and without lube. The density and length of the samples were measured before and after sintering. The changes in density and shrinkage calculations were made from the data. Figure 2 shows green and sinter density sample made from powder without lube. These samples sintered to 100 % density, whereas, samples with lube sintered to somewhat lower density but higher than conventionally processed samples. Similarly, samples made from powders without lube showed the lowest shrinkage (~ 0.5%) compared to conventional shrinkage that ranges between 3.5-4 %. The shrinkage control was very good in DMC fabricated samples showing the feasibility for near net shape fabrication. Figure 3 shows the shrinkage in sintered aluminum samples made from aluminum powders with and without lubes.

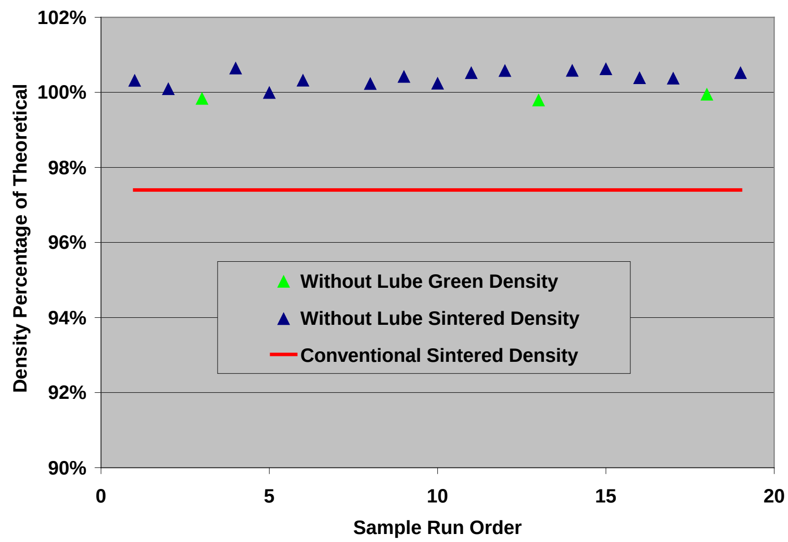


Figure 2: Green and sinter density of DMC consolidated samples from powders without lube relative to conventionally press and sinter samples (shown by solid red line). DMC processed samples showed full density.

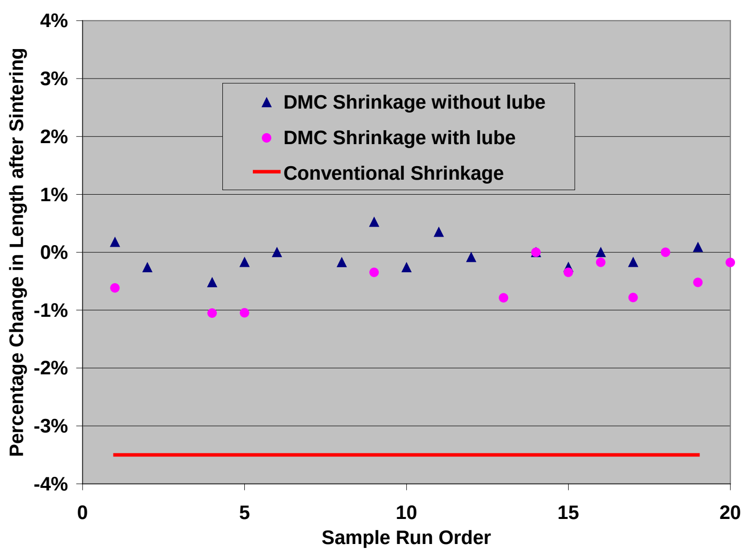


Figure 3: S3hrinkage of DMC processed aluminum alloys without lube showed less than 1/2 % shrinkage. Conventionally processed samples show 3.5 to 4 % shrinkage.

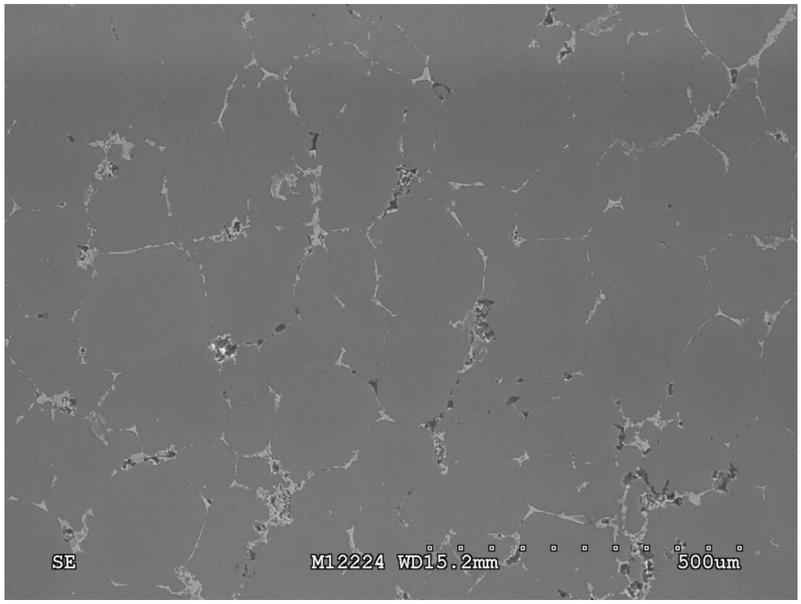


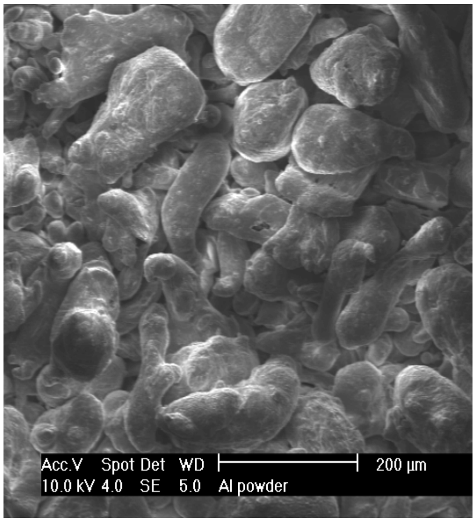
Figure 4: Microstructure of fully sintered aluminum alloy shows good particle to particle bonding. No pores or voids present in fully dense sintered sample.

The microstructure of fully sintered aluminum alloy showed excellent sintering at particle boundaries as shown in Figure 4. The dark spots are $Al_2 O_3$ reduced to MgAlO and there are no voids or pores in the sintered material confirming the density measurements.

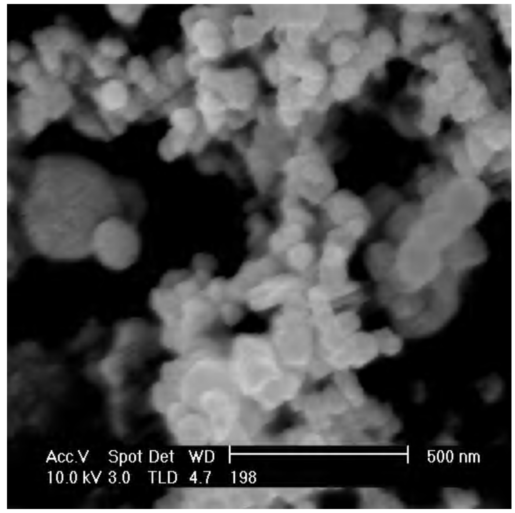
The sintered alloys were heat treated as per conditions prescribed for conventional aluminum alloys of 2000 series. The sintered and heat treated samples had good strength characteristics as measured by tensile tests according to ASTM standard method. The ultimate tensile strength in sintered samples was 27 ksi, yield strength at 0.2% offset was17 ksi and elongation 5 %. The heat-treated samples in T6 condition showed ultimate and yield in the range of 56 ksi with 1 % elongation. These values are higher than conventionally press and sintered P/M samples prepared from the same powders (as reported in AMPAL Inc. powder spec sheets). We believe these values can be further improved by optimizing sintering and heat treatment temperature and cycle time in Phase II. The DMC processed aluminum alloys showed good fracture toughness value of 13 K_{1C} ksi$(in)^{1/2}$ which is close to that of wrought alloy of the same series.

Aluminum Nano Composite Feasibility work:

For composite fabrication, nano SiC powders (20-50 nm) in beta phase were dispersed in aluminum powder matrix (60 micron average size) using a proprietary process. Figure 5 shows the scanning electron micrograph of aluminum powder used for matrix and nano SiC powders for reinforcement. As shown in Figure 5, as purchased nano powders are produced in agglomerated form and simple blending of nano and micron size powders does not yield a homogenous distribution. Under a different SBIR project we invented a dispersion method for nano powders into micron size powders. A patent is applied for such an invention. The same method was used in Phase I to show the feasibility of dispersing nano silicon carbide (SiC) into aluminum powders.



(a)



(b)

Figure 5: Scanning Electron Micrograph of (a) aluminum (200 μm scale) and (b) agglomerated nano SiC powders (500 nm scale). These nanopowders are very hard to handle and need special methods to blend with aluminum powders to make composites.

Using this process, we were successful in obtaining good dispersion of nano aluminum powders in micron size aluminum powders. Figure 10 shows the aluminum alloy powders and nano powders before dispersion and Figure 11 shows the same aluminum powders with nano dispersion. In Figure 6, the fuzzy dust on aluminum powders is due to nano powder coating. These nano composite powders were compacted using DMC process. The composites were sintered at 10 to 20 ºF higher than pure aluminum alloy powders. With these sintering

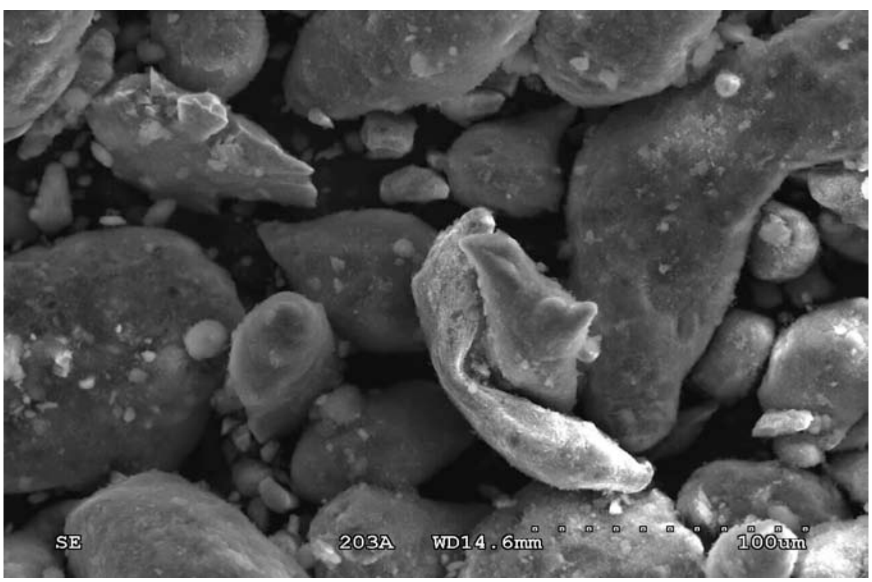


Figure 6: Aluminum powders coated with nano SiC powders (100 μm scale). These Al-nano composite powders are ready to be compacted and sintered.

conditions, the density achieved in the composite was 85-90 % of full density. The composite sintering temperature and time has to be optimized to obtain full density. The sintered microstructure of the composite obtained with the above conditions is shown in Figure 7.

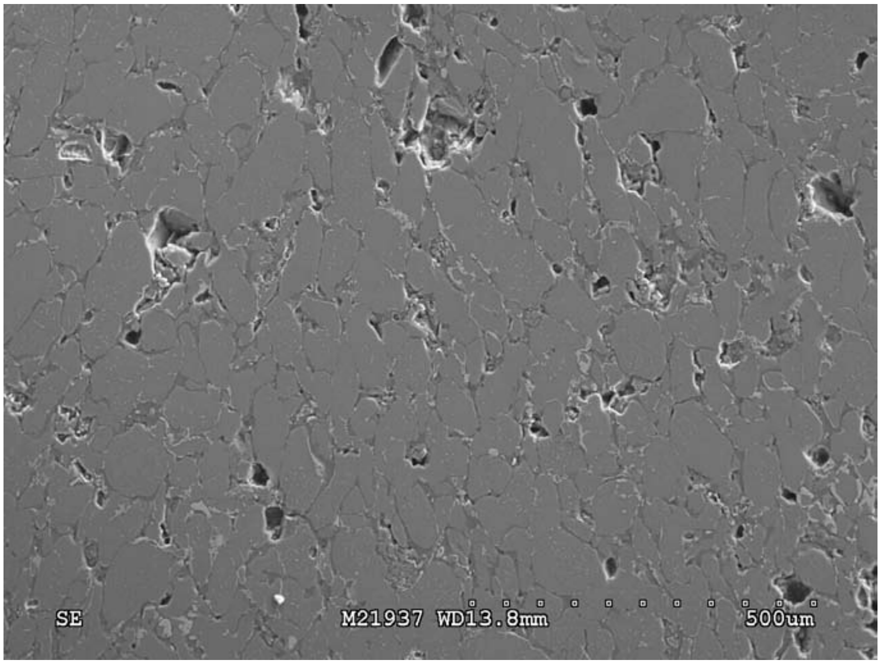


Figure 7: Sintered microstructure of composite material

Summary

During Phase I, we successfully processed air atomized aluminum powders via Dynamic Magnetic Compaction (DMC) pressing and subsequent sintering to produce parts with properties similar to wrought aluminum. We have also showed for the first time that aluminum powders can be processed without lubes via press and sintering to 100 % density. **This will preclude a delube cycle in sintering and promote environmentally friendly P/M processing**. Processing aluminum powders via press and sintering with minimum shrinkage will enable net shape fabrication. Aluminum powders processed via a conventional powder metallurgy process produce too large a shrinkage. Because of this, sinter parts have to be machined into specific net shape. This results in increased scrap and cost. Fully sintered aluminum alloy under this Phase I project has shown good particle-to-particle bonding and mechanical properties.

We have also shown the feasibility of preparing nano composite powders and processing via pressing and sintering. This was accomplished by dispersing nano silicon carbide (SiC) powders into aluminum matrix comprising micron-sized powders (<100 microns) using a proprietary process. These composite powders of Al with nano SiC were processed using DMC press and sinter process to sinter density of 85-90%. The process optimization along with sintering needs to be carried out to produce full density composites.