HIGH RATE MANUFACTURING PROCESS FOR SILICON CARBIDE TILES

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ABSTRACT

Silicon carbide (SiC) ceramic armor is typically hot pressed to obtain full density and superior performance characteristics for demanding applications such as vehicle protection. Hot pressing is however an expensive and slow batch process. This paper describes an alternative, high rate processing approach of Dynamic Magnetic Compaction, which combines a high-density green compaction method with pressure-less sintering. The resulting close to full density material is produced at high throughput and delivers high quality material in near net shape form with a cost advantage. Dynamic Magnetic Compaction has already been successfully applied to process metals, composites, and nano powder products. The successes in these sectors are being translated to the ceramic industry, specifically to process high temperature ceramics such as SiC and BC.

1. INTRODUCTION

SiC-N grade of silicon carbide has been identified as one of the best ceramics for ground vehicle protection. Estimates of the amount of SiC-N required for each ground vehicle for the Future Combat System (FCS) are roughly 3000 – 5000 lbs per vehicle. Although the number of vehicles delivered, either in total or in any particular year are subject to change, currently over 100 vehicles are expected to be delivered in the first full year of production requiring 300,000 to 500,000 lbs of SiC-N.

Silicon carbide (SiC) tile is manufactured by the hot pressing technique. In this approach large slabs of silicon carbide are fabricated in a batch process using high pressure and temperature (> 2000°C) for extended periods. After these slabs are fabricated, 4"x 4" ballistic tiles are cut and ground to the final product specifications. Each batch requires at least four days to process and produces approximately 400 pounds of tiles. It follows that at this rate, it would take 15-20 years to fulfill the production capacity for the first 100 vehicles!

The development of an alternate high-rate processing technique that combines a fast, high-density compaction process (DMC) with pressure-less sintering to produce SiC is in progress. Results on SiC material produced via such a process are described in this paper. Relative to current hot pressing methods, this manufacturing technique is estimated to reduce the cycle time for ballistic tile fabrication by nearly an order of magnitude.

2. BACKGROUND OF DYNAMIC MAGNETIC COMPACTION (DMC) PROCESS

Dynamic Magnetic Compaction (DMC) has been developed by IAP Research Inc based on two decades of experience in electromagnetic rail gun technology. In DMC, the pressure generated by pulsed magnetic fields is used for powder consolidation. The resulting forces can be generated either in the radial direction for compacting cylindrically symmetric shapes or in the axial direction for compacting flat shapes such as rectangular or square plates. Parts of near- to full-density are formed in a timeframe of less than a millisecond. DMC has been successfully used to process various powders including metals, ceramics, composites, and nano materials. These Powder Metallurgy (P/M) products that are fabricated with DMC encompass a broad range: from automotive power train gears using steel powders to higher performance motor components using magnet powders. Figure 1 shows typical structural and motor products made by the Dynamic Magnetic Compaction process which are ready for commercialization. All of these parts have cylindrical symmetry and are produced using the DMC radial compaction technique.

Figure 1(a) and 1(b) show some of the automotive components made via the DMC process. In the automotive industry, there is a demand for close to full density parts such as power train gears for high performance applications. Currently such parts are machined from wrought and forged blanks. Due to high machining costs, these parts are much more expensive than conventional press and sinter P/M parts. DMC

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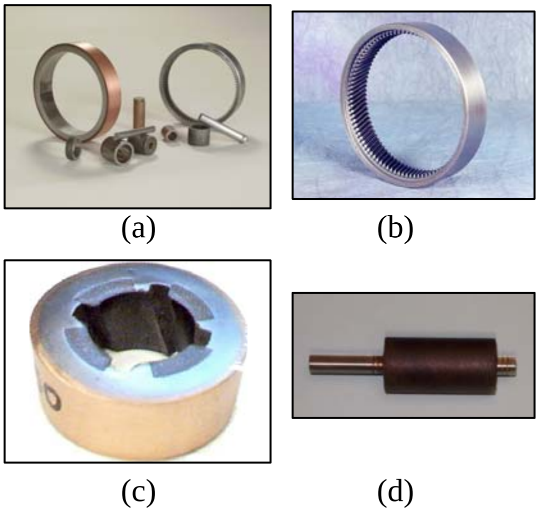

Fig. 1. (a) Automotive parts via DMC, (b) DMC Powertrain gear, (c) DMC stator, and (d) DMC rotor.

produces high density parts at a cost of a single press and single sinter process. Figure 1(b) shows DMC fabricated power train gear of AGMA 9 rating. The gear teeth were net shape formed to full density. No secondary operations were required on the teeth after sintering. This is the first time an AGMA 9 gear is produced via P/M processing.

Similarly, in defense and commercial applications, high power density motors are required for size and weight reduction. In conventional motor manufacturing, magnets are made separately and attached to the motor frame during the assembly process. In contrast, DMC motors are formed in a single step directly from magnet powders yielding higher performance and manufacturing cost savings. Due to high density that is achieved in the magnets, DMC motors are compact with respect to size and weight. The rotor in Figure 1(d) yielded 33 % improvement in torque density or 12 % reduction in size over a conventional rotor of the same design.

As a rapid process of sub millisecond duration, Dynamic Magnetic Compaction (DMC) also has proved to be very beneficial for processing nano powders into bulk components while suppressing grain growth. For the first time we have demonstrated that high strength titanium nano composites can be processed from nano powders. These composites are targeted for replacing 4340 steels in bearing applications. The following paragraph gives a brief summary on titanium nano composite material.

In the case of nano powders, DMC densification offers the benefit of minimal or no grain growth due to the sub-millisecond compaction time that is followed by a short and low temperature-sintering schedule. Using this approach, we have processed titanium nano composites with properties close to that of steel for replacing steel bearings. Pure titanium metal has a hardness in the range of 30-35 HRC, whereas, titanium nano composite developed at IAP exhibited hardness of 60 HRC- twice that of the pure metal. In addition, the hardness enhancement due to nano size particulate reinforcements is 30% better when compared to composites made using micron size reinforcements. Other properties such as modulus, strength, and wear resistance are also enhanced with increasing concentration of nano reinforcement in the matrix.

The Dynamic Magnetic Compaction method has demonstrated to be a sustainable, high throughput and robust manufacturing method for metallic P/M products with energy and cost savings. The payoff of DMC processing for ceramics, especially silicon carbide armor tiles, is currently being investigated.

2.1 DMC Processing of SiC

We are presently extending our DMC knowledge base on processing metallic materials to ceramics, specifically, armor grade SiC. Silicon carbide processed via DMC and Pressure-less sintering (PS) will be hereafter referred to as DMC-PS material.

SiC powders from Superior Graphite - 490 NDP with binders and lubricants with BC as a sintering aid was used in the following feasibility study (Chelluri et al., 2005). It was demonstrated that density close to full density (> 98.6 %) of DMC-PS SiC can be achieved using these powders.

The microstructure of DMC-PS SiC material is shown in Figure 2(b). The DMC-PS SiC microstructure was found to be very uniform with small (3-5 micron) grain sizes similar to pressure assisted densification (PAD) SiC material. Figure 2(a) shows the

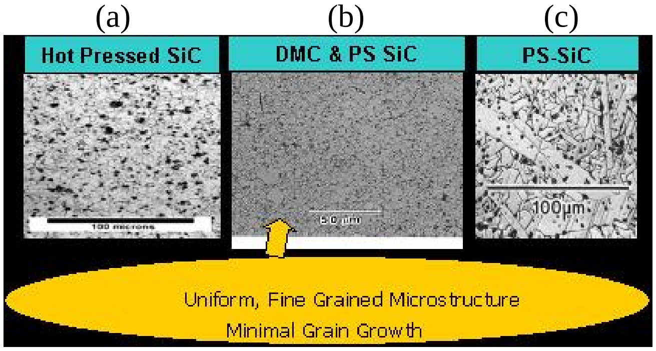

Fig. 2. (a) Etched microstructures of PAD SiC*, (b) DMC-PS silicon carbide, and (c) conventional pressure less sintered (PS) SiC* that reveal large grains and pores in PS-SiC.

*T. Liallo, H.Chu: Idaho Engineering and Environmental Laboratory microstructure of hot pressed (PAD) SiC material. DMC PS material in Figure 2(b) is similar to the hot pressed material. Figure 2(c) shows the microstructure of conventional pressure-less sintered (PS) SiC material. The long 10-15 micron elongated grains evident in the microstructure of conventional PS-SiC material were absent in DMC-PS SiC samples. Relative to conventional PS-SiC samples, the DMC-PS microstructure clearly shows uniform grain and pore distribution.

The feasibility of optimizing the mechanical properties of DMC-PS SiC samples for obtaining properties similar to PAD SiC-N was established through measurement of the modulus and Poisson's ratio of DMC-PS SiC. These measurements were based on Resonant Ultrasound Spectroscopy (RUS) and confirmed that the mechanical parameters of DMC-PS SiC samples were in the same range as those of PAD SiC-N material. The elastic modulus value (E=430 GPa) and Poisson's Ratio (ν=0.19) were measured on DMC-PS material with 98.4% of theoretical density. In comparison Cercom PAD SiC-N material has E=460 GPa and ν=0.16 (Lee et al., 2005). Achieving these mechanical properties via pressure-less sintering that lie in the proximity of those for hot pressed specimens is a significant advancement.

Vickers hardness measurements were made on DMC-PS SiC samples of two different sintered density values. Figure 3 shows the expected increase in hardness numbers with density of the DMC-PS SiC samples. DMC-PS samples of 96 % density exhibited hardness of 3400 VHN whereas hot pressed (hot Pressed at 2100°C/27.5 MPa/1 Hour) samples of density 99.2 % showed hardness (Cutler, 2005) of 2621 VHN. Conventional pressure-less sintered samples (sintered at 2150°C/0.5 hour) had hardness of 2549 VHN. Thus DMC samples showed highest hardness. Toughness measurements on DMC-PS SiC are under progress. The combination of high hardness and toughness is desirable for armor properties. Further enhancement in hardness (3500 VHN) is obtained in samples processed with SiC nano powders as shown in Figure 3.

The shrinkage of DMC-PS SiC specimens was measured for a large batch (60) of samples and confirmed that the contraction was uniform from part to part with only a 0.2% standard deviation. Further, the average shrinkage of a part was reduced to 11% in DMC-PS SiC parts relative to 16% shrinkage in conventional PS SiC parts. We believe, with such a predictable and uniform shrinkage, net shape armor tiles can be fabricated by the appropriate compensation in tooling.

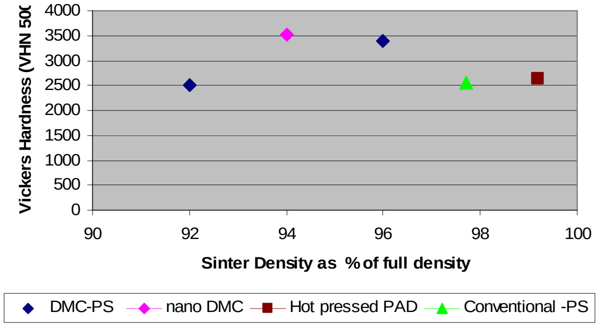

Fig. 3. Vickers hardness of DMC-PS SiC, PAD, and conventionally pressed samples versus sinter density. Consolidation with nanopowder SiC enhances hardness.

2.2 DMC Radial and Flat Compaction

Dynamic Magnetic Compaction technology is a patented process (Chelluri et al., various), where pressure generated by pulsed magnetic fields is used to compact powders to a very high green density in a time frame of less than a millisecond. These green compacts of density greater than 70% are pressure-less sintered for short periods at lower temperature without grain growth. Figure 4(a) shows a schematic of such a process for pressing net shape cylindrical parts, and Figure 4(b) for pressing flat parts.

The basic principle of the DMC process is shown in Figure 4(a). In this method, a conductive container (armature) is filled with powders and placed in the bore of a high field coil. The coil is pulsed with a high current to produce a magnetic field in the bore that, in turn, induces currents in the armature. The induced currents interact with the applied magnetic field to produce an inwardly acting magnetic force that collapses the tube, thereby compacting the powder. The armature is launched into the powders with a large kinetic energy. The powders are pressed to full density via the transmitted impact energy with the entire compaction occurring in less than a millisecond.

In the flat compaction system, the top and bottom sets of arrows indicate pressure generated via magnetic fields. The uncompacted powder column at the start of the process is shown in the top half of Figure 4(b). After compaction, the powder column density increases due to the applied pressure while the length of the column reduces to a new value as shown in the bottom half of Figure 4(b). With such a set up, flat plates of rectangular and square shape can be pressed to high density. Such a system will be used to fabricate SiC armor plates.

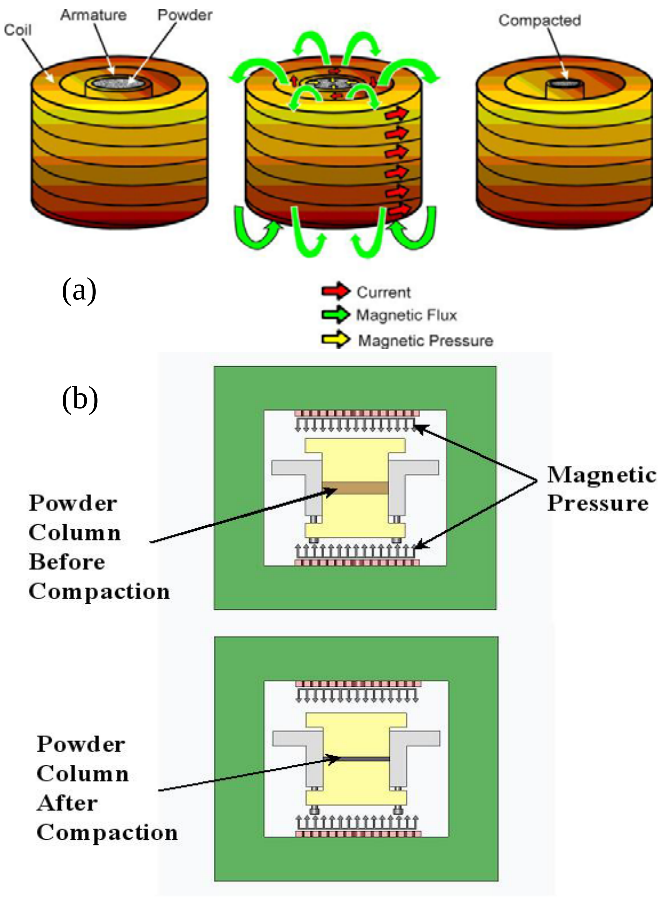

Fig. 4. DMC Armatures: (a) radial compaction, (b) flat compaction.

In the DMC-PS process, the pressure-less sintering time was reduced to <10 hours for SiC processing compared to the 96 hours needed with the PAD process. Thus, DMC based PS processing of SiC can be made into a low cost, semi-continuous, high-rate production method for armor tile production. Figure 5 illustrates this concept to incorporate DMC and pressure-less sintering into SiC tile processing technology.

In Figure 5, the powder station is shown where powders are filled in the cassette. Next, this cassette is inserted into the DMC press for compaction, and then the green part is extracted from the cassette and sent for pressureless sintering as shown. As sintering times are optimized to be less than 5 hours, the process can be made into a semi-continuous process.

3. SUMMARY AND CONCLUSIONS

The DMC technique with pressure-less sintering for processing high performance SiC in a semi-continuous mode is described. Characteristics of SiC via DMC-Pressure-less sintering are compared to hot pressed SiC-N material. A brief summary of technical and commercial successes demonstrated with metallic and magnetic products via DMC is described. Benefits of DMC for processing nano powders are also described.

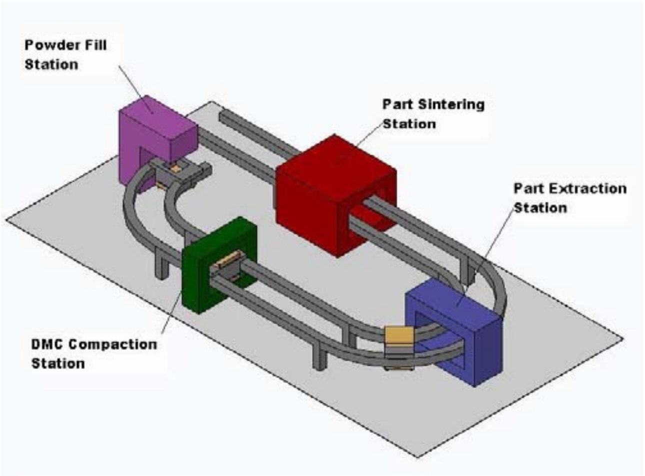

Fig. 5. Semi-continuous processing route for SiC armor tile fabrication via DMC-PS process.

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