Powder Forming Using Dynamic Magnetic Compaction

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Abstract

Conventional powder forming of metals, ceramics and composites uses room temperature pressing approaches such as static uniaxial pressing, isotropic pressing - cold isostatic pressing (CIP) or elevated temperature hot isostatic pressing (HIP) methods. In this paper, description of a unique dynamic pressing approach for powder materials will be presented where very high pulse pressures (of GPa range) are applied for a short duration (of < 1 millisecond) on powders. Such a dynamic pressing offers the ability to form uniformly high density net shape parts with fine microstructures. The method can be applied to wide range of materials such as metals, ceramics, composites and soft and hard magnetic materials. A broad range of powder particle size distributions, from coarse micron size to fine nano size powders, can be used in the process. The principles of dynamic pressing method along with the summary of results on various powder material systems will be presented. The performance of parts made with dynamic method will be compared with conventional processes.

Keywords

Powder, Near net shape, Dynamic

1 Introduction

In the Powder Metal (P/M) industry there is a constant demand for producing high-density net shape parts at an affordable cost. In the commercial sector such as the auto industry, there is a need for close to full density parts such as power train gears for high performance applications. Currently such parts are machined from forged and wrought blanks. Due to high machining costs, these components are much more expensive than conventional press and sinter P/M parts. The conventional single press, single sinter process (including warm pressing) produces steel parts to low density of only about 6.9-7.4 g/cc. Similarly, high performance ceramics such as ballistic tiles are produced using hot pressing (Pressure Assisted Densification- PAD) process or Hipping (HIP). Both PAD and HIP are batch processes, have low throughput and are expensive due to inherent time and secondary processes involved in producing the final tile shape. Various other powder materials such as permanent magnet powders for electric motor applications, thermoelectrics for efficient heating and cooling devices and nano structure powder materials with special microstructures require processing methods that preserve the properties of original powders while yielding high density and net shape for cost reduction.

This paper describes a high rate dynamic powder pressing approach that uses pulse magnetic pressures to compact the powders [1]. In dynamic magnetic compaction (DMC) processing, kinetic energy is imparted to powder material using magnetic fields in a sub millisecond time duration. DMC compaction pressures of a few GPa range on powders produces high green compact density. The development of DMC technique for ductile metallic materials has been demonstrated and implemented for net shape geometries such as gears [2] and cylinders. However, in the case of brittle ceramic powders, the compacted material can develop cracks during the release of internal strain energy during rebound. IAP Research, Inc. has developed an innovative design of a dynamic compaction system to control rebound energy and produce crack-free high performance ceramic parts [3]. In the following paragraphs, general process description along with selected examples of parts fabricated and their properties will be described.

1.1 Dynamic Magnetic Compaction (DMC) Process

The basic principle of the Magnepress^{TM} DMC process is shown in Figure 1. In this method powders are filled in a conductive container (armature) 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 launched armature accumulates a large kinetic energy during compaction and is brought to rest by the powders within a few microseconds. The powders are pressed to full density via the transmitted impact energy with the entire compaction cycle occurring in less than one millisecond.

Magnetic forces have been used for over two decades in high rate metal forming [4] and powder compaction [5]. The same electromagnetic based pulse forces are used in DMC process to realize net shape powder consolidation. The powder pressing in DMC takes place through the transmitted impact energy analogous to driving a nail into a board with a hammer. Almost any material can be compacted to full density using a sufficiently large impact pressure. The important benefits of magnetic powder compaction are higher green (compaction) density, high aspect ratio (L/D) compacts when compared to die pressing and ability to preserve special microstructures.

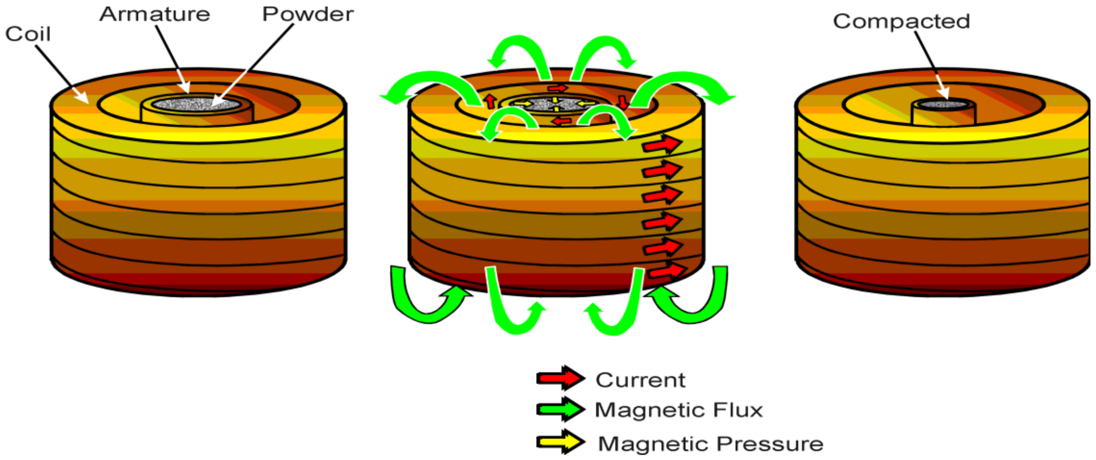

Figure 1: *Principle of DMC process*

The process steps of powder processing using DMC process are shown in Figure 2. These steps are similar to conventional P/M pressing which include tooling for compaction, powder filling, part extraction and sintering with the optional steps of sizing and finishing as required. In most commercial applications the powder filling and compaction are done in air at room temperature. The powder filling can be carried out in special environments such as in an inert gas or under other cover gases for special applications and can also be compacted at elevated temperatures with suitable system modifications.

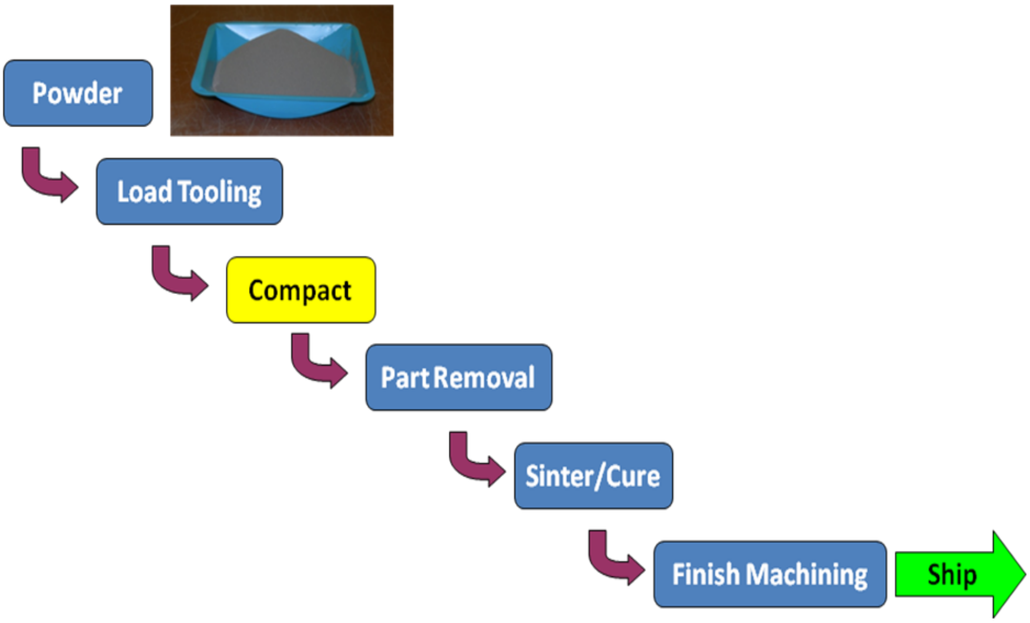

Figure 2: *Dynamic Magnetic Compaction processing steps*

2 Dynamic Magnetic Compaction Processing

2.1 Densities of ferrous and non ferrous alloys processed via DMC Magnepress™

Many different alloys of ferrous and nonferrous powders can be consolidated using magnetic pressing. Figure 3 shows the as pressed density achieved in various powder materials. No lubricants were added to any of these powders. In most steels, densities greater than 95% were achieved after DMC compaction.

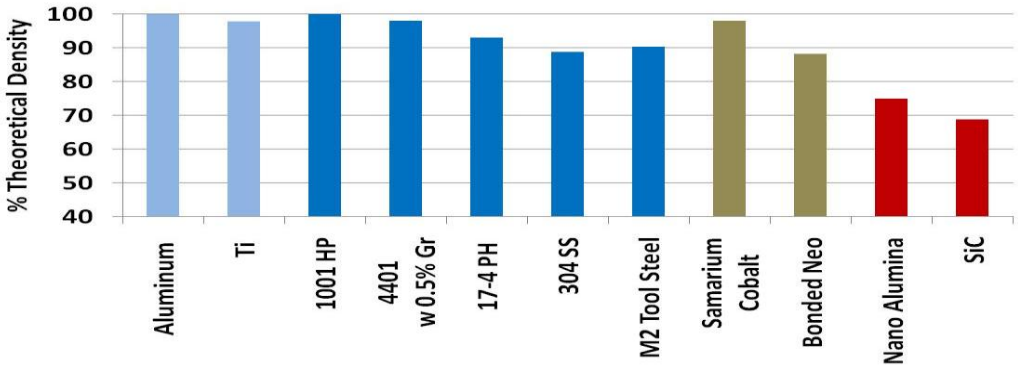

Figure 3: L*ist of materials compacted with the DMC process and the green density achieved*

In the 4405 alloy (4401 with 0.5%Graphite), the green density was greater than 97% of full density. The processes used for some alloys indicated in Figure 3 were not optimized and higher densities can be obtained with further development.

2.2 DMC Density Improvement Boosts Material Performance

The mechanical and microstructural properties of materials are positively affected by DMC processing.

2.2.1 Material Properties of DMC Processed 4405 Steel Alloys

A systematic evaluation of the material properties was carried out with 4405 steel powders. Rods were DMC compacted using 4405 powders at different pressures and sintered at 1180ºC (2156ºF) for 20 minutes in dissociated ammonia. The density and mechanical property measurements were made using ASTM standards. The measured mechanical properties such as transverse rupture strength, tensile, hardness and unnotched impact energy were measured and results were close to those of wrought material of the same composition. The transverse rupture strength of DMC green samples was higher than that of conventional pressed specimens as evident from Figure 4. In Figures 5 and 6, the tensile strength and ductility of DMC samples are summarized along with those of conventionally pressed P/M and malleable cast iron. Tensile and yield strength of DMC materials are higher than conventionally pressed material and closer to the properties of cast material. Tensile elongation of DMC material is 4-6 %, which is similar to that of cast samples. The impact energy of (unnotched) DMC bars is 60 ft-lbs as shown in Figure 7.

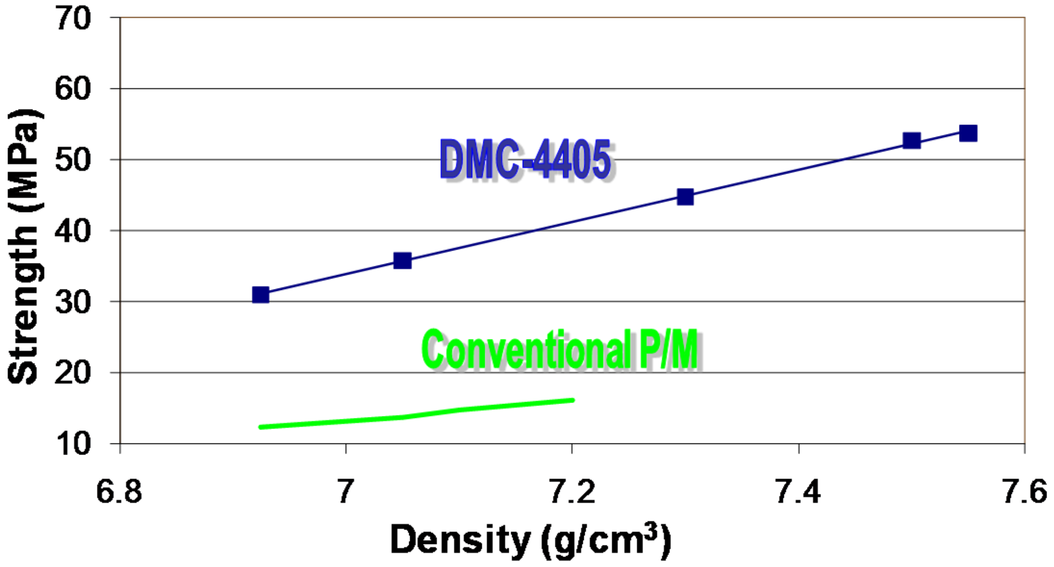

Figure 4: *Transverse Rupture Strength of DMC processed 4405 material compared to conventional P/M*

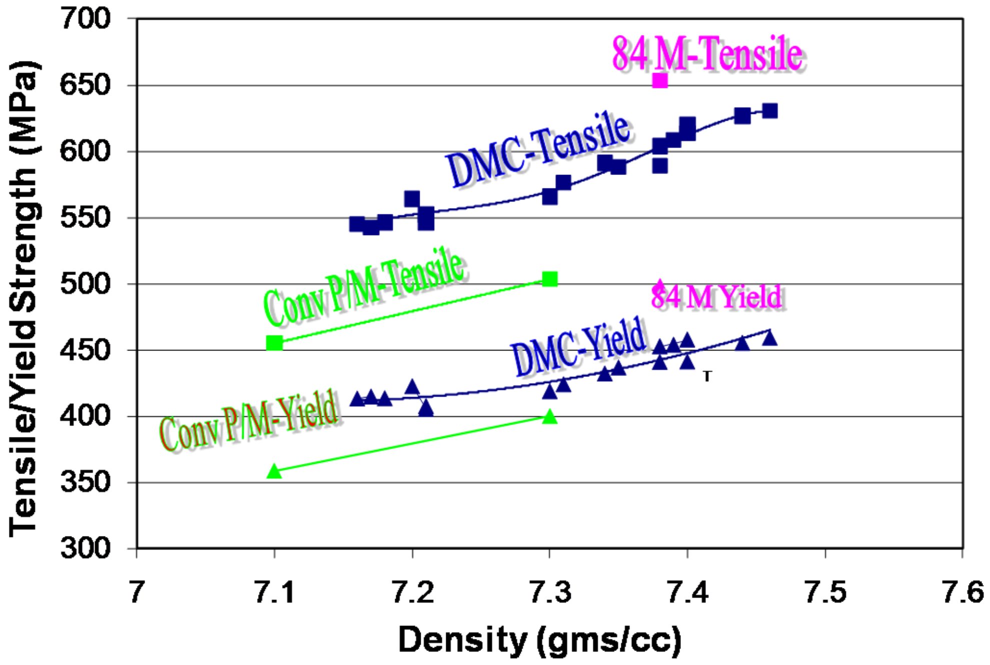

Figure 5: *Tensile and Yield strengths of DMC processed material as compared to 84M-malleable cast iron (2.5% nodular carbon)*

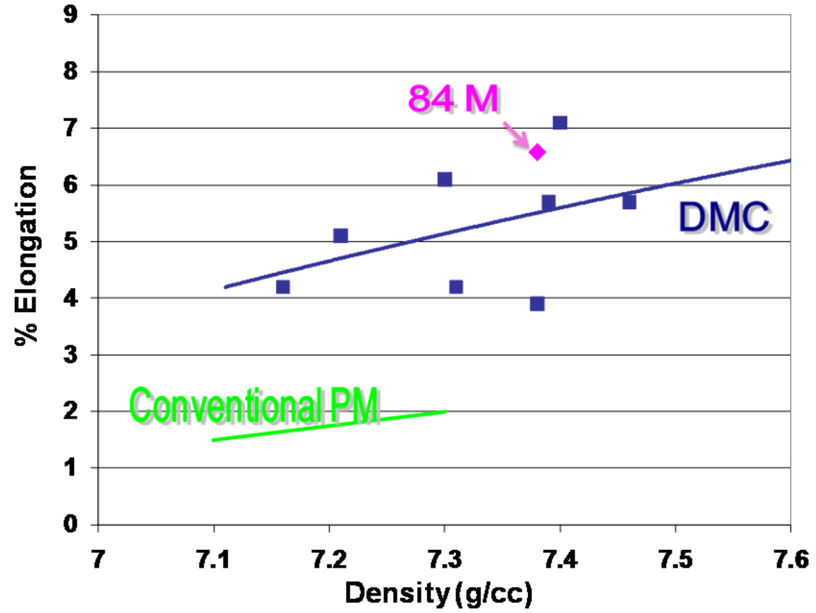

Figure 6: *Ductility of DMC processed 4405 alloy relative to conventional P/M 4405 and malleable cast iron (84M)*

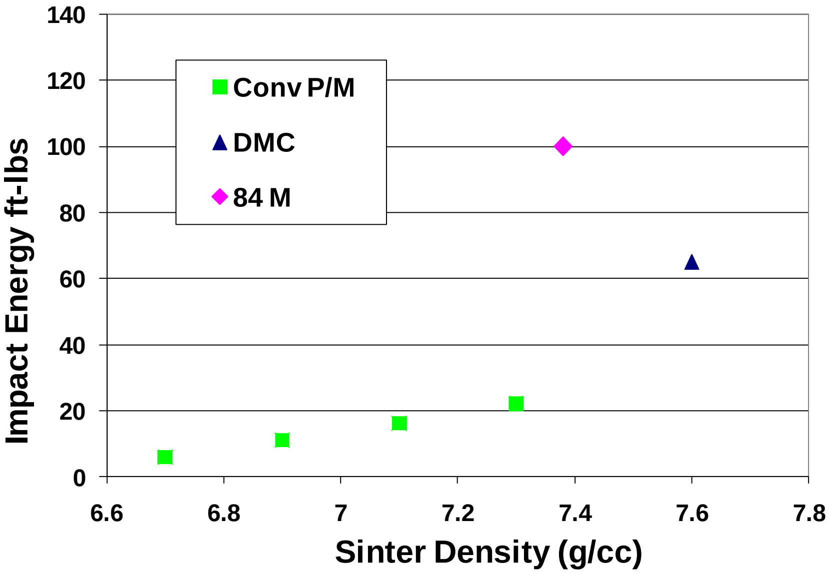

Figure 7: *Unnotched impact energy of DMC processed sample*

2.2.2 Microstructure of DMC Processed Materials

In addition to high density, the other benefits of DMC arise from its dynamic nature of sub-millisecond compaction. This feature aids in preservation of special microstructures including ultra fine grain size. One such example shown in Figure 8 where samarium cobalt magnetic powders (3-6 µm grain size) were compacted using two different compaction methods, cold isostatic press (CIP) and DMC magnetic pressing. Both of samples were subjected to the same sintering cycle side by side in the same furnace. Figure 8 shows the dramatic difference in microstructures in sintered CIP and DMC samples. The DMC sample retained the fine grain structure of the starting powders while the CIP samples showed increase in the grain size to 200 µm after sintering. The starting green density was 65% for CIP and 85% for DMC respectively. Similar results are observed in processing of silicon carbide ceramics. The mechanism of retention of fine grain structure in DMC compacted sample is not fully understood and still under study.

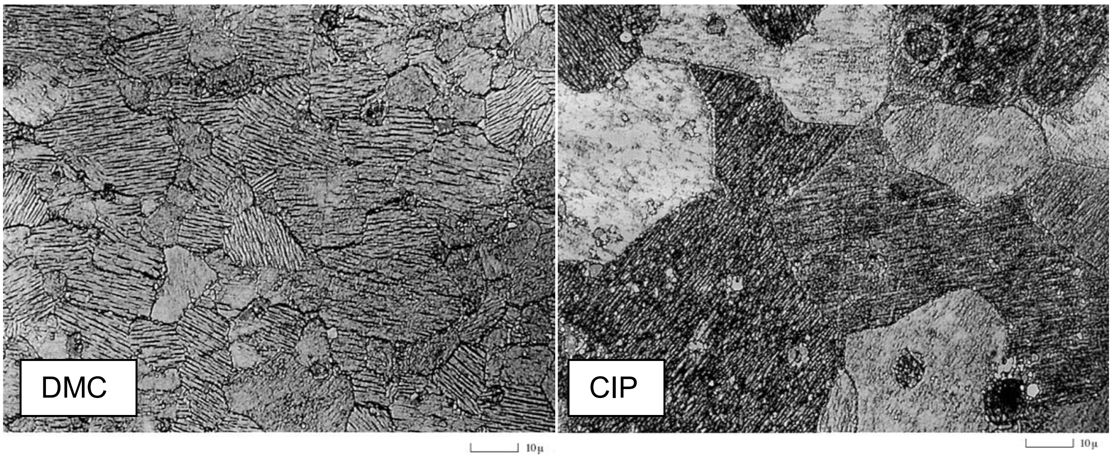

Figure 8: *Scanning electron micrograph of Samarium Cobalt powders compacted by DMC and CIP and then sintered under the same conditions*

2.3 Shapes and sizes of net shape parts via DMC

The radial DMC process is ideally suited to produce net shape parts with cylindrical symmetry, thin walled tubes, high aspect ratio (L/D) parts and parts with internal features. Shapes and sizes of the typical parts produced to date range from 0.5“ diameter x 3“ long to 5” diameter x 1“ long as shown in Figure 9. The helical ring gear, shown in Figure 9, achieved an AGMA 9 precision rating after sintering without any secondary operations on the teeth. A DMC system can produce flat parts such as rectangular parts shown in Figure 10.

Figure 9: *Typical shapes of the parts produced via radial DMC process*

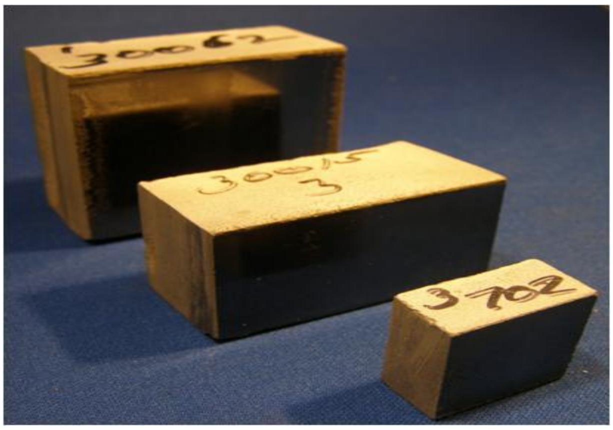

Figure 10: *Typical shapes of the silicon carbide parts produced via axial DMC process*

2.4 DMC Production Rates and Process Repeatability

Given a compaction cycle of the magnetic press at less than 1 millisecond, the production rate of five to fifteen parts per minute (ppm) can be achieved. The two factors that limit the production rates are the power supply charging time and the material handling rates such as insertion of powders and removal of part from the press. Our commercially available power supply module is rated for 15 discharges per minute. Power supply designs for faster than fifteen per minute are possible if required. Material handling rates are controlled by powder filling, part extraction, and transfer rates. DMC processing has demonstrated multi-part per pulse output for some parts.

The DMC process is highly repeatable. The amount of energy discharged into the part can be tightly controlled and measured for statistical control evaluation. The Magnepress^{TM} DMC process also draws benefit of compacting different types of powders such as spherical, flakes, and coated powders without damaging special aspects of the starting materials. No binders or lubricants are required for compaction.

3 Conclusions

The Magnepress^{TM} DMC process holds potential for expanding P/M markets into full density and high performance products. The process feasibility is demonstrated for various powders of ferrous, non-ferrous, ceramic and composites. The development of specific prototype parts with steel powders for automotive industry, electric motor parts and ceramic parts have been accomplished. Other product applications with different powder materials are being investigated.

References

[1] Chelluri, B., Barber, J.B., inventors. United States Patent Nos.: 5,405,574; 5,611,139; 5,639,797; 5,611,230.

[2] Barber, J.B., Bauer, D., Chelluri, B., Knoth, E., et.al. Dynamic Magnetic Compaction (DMC) for high power density helical gears. Proceedings of MPIF World Congress, Vancouver, BC, June 21-24 1999.

[3] Chelluri, B., Knoth, E., Schumaker, E.. Method for Producing SiC Armor Tiles of Higher Performance at Lower Cost. Proceedings of The 34th International Conference on Advanced Ceramics and Composites, Daytona Beach, Jan 24-29 2010, Daytona Beach, USA.

[4] Meyers, M.A., Murr, L.E., editors. Shock Waves and High Strain Rate Phenomena in Metals, Plum Press, N.Y. p. 913-1019.

[5] Gourdin, W.H., Dynamic Consolidation of Metal Powders. Progress in Materials Science, Vol.30, 1986, p. 39-80.

[6] Mamalis, A.G., Manolakos, D.E., Electromagnetic Forming and Powder Processing: Trends and Developments, Appl. Mech. Rev., July 2004, Vol. 57 N.4, p. 299-325