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METAL ALLOYS, INTERMETALLICS, AND COMPOSITES BY
HOMOPOLAR GENERATOR DISCHARGE**

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SINGLE RESIDENCY SINTERING AND CONSOLIDATION OF POWDER METAL ALLOYS, INTERMETALLICS, AND COMPOSITES BY PULSED HOMOPOLAR GENERATOR DISCHARGE

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SUMMARY

Utilizing inertial energy storage the homopolar generator (HPG) is capable of delivering multimewatt, megampere current pulses into resistive or inductive loads with high efficiency.(1) Such HPG's have been used for many years as power supplies for research in pulsed processing of metal alloy components and systems. Most of these processes rely on extremely rapid thermal excursions in the workpiece(s) caused by resistive heating during the current pulse. A new application of pulsed HPG's that carries great promise is homopolar pulse consolidation (HPC) of powder metal alloys or components.(2) In HPC, powder metal constituents are loaded into a thermally and electrically insulated die, then precompacted to an initial pressure. The "rams" of the compaction press are also the electrodes for homopolar discharge current. While in single residency, the powder compact is heated uniformly by HPG discharge current, sintering occurs, and consolidation is accomplished by hydraulic control of the consolidation press. The process is completed in approximately one sec, with unaided cooling to room temperature on the order of 100 sec, depending on compact mass. Microstructural control is closely tied to beginning particle size and distribution. Traditionally unsinterable alloys have been consolidated using HPC. Novel intermetallic alloys and phases have been produced. Cermets and other composites can be produced, as long as the continuous matrix is conductive. New tooling designs allow for controlled atmospheres, near-net shapes, and automated manufacturing.

INTRODUCTION

The Center for Electromechanics at The University of Texas at Austin (CEM-UT) has investigated novel pulsed electric generators since 1972. Chief among these is the iron-core (ferromagnetic) pulsed homopolar generator (HPG).(1) The homopolar effect, discovered and described by Michael Faraday in the 1830's, is characterized by a voltage gradient generated in a conducting rotor that spins in a uniform magnetic field. The open circuit voltage thus created is given by:

$$v = \frac{\omega \phi}{2\pi}$$

where ω is angular speed in radians per second, and ϕ is magnetic flux in Webers. Typically, HPG's are low voltage, low internal impedance devices. In a pulsed HPG,

energy stored in the rotor due to its angular velocity is converted into electric energy in an external circuit as the reacting torque brakes the rotor to a reduced speed, or to a stop. The electric current pulse is characterized by a rapid rise to peak (approximately 50-100 ms), followed by a first order exponential decay to zero, over a pulsewidth of from 0.5 to two or more seconds. Depending on generator parameters and external circuit characteristics, with an HPG of 1 t mass, this pulse can be greater than one megampere peak current with an average power of tens of megawatts.

CEM-UT has developed and operated numerous HPG's for a wide range of applications.(3) Because of the high available power, HPG's are ideal sources for rapid joule heating of resistive workpieces. For this reason, along with their reliability and ease of operation and control, HPG's have been studied as pulsed power supplies for various industrial applications, including homopolar pulsed welding and homopolar pulsed heating .(4) A 10 MJ, disk type, pulsed HPG system at CEM-UT (figure 1) has been dedicated to such pulsed processing research since 1976. This is the system in which sintering and consolidation of powder metal (PM) alloys, in single residency, is currently under development.

Figure 1. 10 MJ Homopolar Generator Research System at CEM-UT

BACKGROUND

Conventionally, PM alloys are processed into monolithic shapes by a series of process steps that usually involves pre-compaction, sintering, pressing, subsequent hot and/or cold working, and "healing" to reduce residual porosity. Final consolidation of finished parts is accomplished normally by hot isostatic pressing, during which the workpiece is held at elevated temperature and pressure for as long as hours. Sintering refers to the diffusion-driven process by which precompacted "green" products, under application of heat and pressure, consolidate as nucleation and growth occur between neighboring powder particles. The driving potential for this solid state phase transformation is the free surface energy associated with the total powder particle surface area in the compact. The sintering process represents the largest energy requirement in conventional PM processing.(5)

For this reason, researchers since World War II have concentrated their efforts on developing solid state, direct heating sintering processes as a means of reducing PM costs while improving productivity. Some of these high energy rate processes use "activation" of the powder through chemistry and morphology control;(6) most rely on joule heating of the powder by electric current. Jones, Cremer, and Ross independently studied the application of welding power supplies to direct sintering and compaction of PM parts in the late 1940's.(7) Regulated alternating current was tested as a sintering power supply at Rensselaer Polytechnic Institute shortly thereafter.(ibid) A Japanese process was licensed to the Lockheed Corporation in the late 1960's for a process called "spark" sintering, in which alternating and direct current were staged independently (and simultaneously) for the production of beryllium-copper parts and tungsten rod and wire.(8) These processes produced parts ranging from 5.0 to 23.0 cm in diameter that required from 3.0 to 19.4 kA/cm² current density for times ranging from tens of minutes to tens of seconds. Spark sintering has produced parts as large as 31.8 kg. All these processes involve multiple step procedures, including, in most cases, post-sintering work to increase density, or heat treatment.

In the 1970's, researchers at The University of Texas at Austin (Chou, et al) investigated single residency sintering and consolidation of copper-graphite composites under direct heating by nickel-iron battery discharge.(9) In these experiments, low voltage battery pulses were conducted through the rams of a double acting die at relatively modest current densities (276 A/cm²). The low power available from the battery bank necessitated consolidation times in excess of 30 s; however, densities in excess of 93% were achieved with good mechanical and tribological properties as compared to similar composites consolidated by conventional processes. This research indicated that the HPG, with higher available current and power than batteries, as well as lower source impedance, would be a suitable power supply for sintering.

HOMOPOLAR PULSE CONSOLIDATION

Homopolar pulsed consolidation (HPC) is a process whereby the discharge current from a pulsed HPG is conducted through a compacted PM load, under pressure, such that the pressurizing rams are also the conducting electrodes for the discharge current (figure 2). A ceramic lining in the bore of the die serves to insulate, electrically and thermally, the compact from the surrounding structure. The PM product is loaded into the die at ambient conditions and pressurized to a state in which interparticle resistance favors very rapid microwelding of particles upon initiation of HPG current. This is where HPC departs from traditional direct means of sintering and consolidation. Because the HPG discharge pulse is unidirectional, the skin effect, or depth of penetration, associated with high frequency alternating current, is minimized or eliminated, resulting in uniform current distribution in the cross section of the compact (assuming uniform pressure distribution within the die). Thus heat generation and resulting temperature excursions are uniform and the resulting sintering reaction, being very rapid, is essentially adiabatic. The volumetric change associated with consolidation is compensated by fast response hydraulic control of the consolidation press, such that applied pressure remains relatively constant during the transition. Therefore, consolidation of the PM part is accelerated by plastic deformation of the powder particles, greatly reducing the time required for conventional consolidation processes. Radial thermal gradients within the die are controlled by conventional powder press considerations to reduce sidewall effects on axial pressure distribution, and the thermal characteristics of the ceramic lining. Axial thermal gradients can be regulated by choice of electrode or interelectrode spacer material such that the thermal boundary conditions in the axial direction do not represent a heat source or sink to the compact. Because of the rapid thermal excursion, both in heating and cooling, final microstructure is linked closely to beginning particle size and distribution, making tailored as-consolidated properties achievable. If post-consolidation heat treatment is necessary for physical property control, this can be accomplished in-residency by post-pulsing of the HPG via field excitation control based on preset values or temperature feedback signals. In general, controlled atmospheres are not required because of the short process duration, but purged or evacuated conditions do not present significant design problems. Material handling between initial compaction and final part ejection is minimized or eliminated.

The HPC system is represented schematically in figure 3. An iron core pulsed HPG is motored externally (generally by closed loop hydraulic drive systems) to a discharge speed appropriate for the mass of PM load material. Upon freewheel (coasting) of the rotor and excitation of the magnetic field, the external circuit is closed by actuation of the sliding contacts or a discrete making switch. The subsequent discharge current pulse delivers high-rate energy to the compact by direct (joule)

Figure 2. Schematic of HPC Die

heating, and sintering occurs rapidly. Displacement sensors track the consolidation of the compact and pressure regulators are used to control the hydraulic press. In-situ temperature measurements within the compact are accomplished by fiber-optic isolated thermocouple leads so that the magnetic and radio frequency fields associated with current passage through the compact do not cause interference. Process parameters recorded include compact pressure, voltage, current, temperature, and axial consolidation, as well as HPG operational parameters.

RESEARCH RESULTS

A wide range of materials, from lightweight aluminum-ceramic alloys to refractory alloys, has been consolidated by HPC with very promising results.(10) It is apparent that any material mixture can be heated and consolidated by this process as long as the continuous matrix through the compacted mixture is conductive. As-consolidated mechanical properties usually depend, in addition to processing parameters, on prior powder particle conditions and environments.

Figure 3. Homopolar Pulse Consolidation System Schematic

Aluminum Alloys

Numerous aluminum alloys have been tested in HPC, most notably ALCOA X7091™.(11) As-consolidated density in this alloy reached 98% of theoretical without localized melting. Also, numerous SiC-reinforced aluminum alloys have been studied. These composites, being cermets, heat and consolidate more readily than does pure aluminum, because of their higher resistivity and lower thermal diffusivity. However, as with similar materials consolidated by other means, post-consolidation hot or warm work is required to restore room temperature ductility. A typical as-consolidated aluminum compact is shown in figure 4.

Copper-Graphite

Extensive research has been conducted in the processing and applications for copper-graphite alloys at CEM-UT since Chou's battery powered experiments. Wang, et al, have developed a copper-graphite HPC alloy that is chemically similar to available commercial grades, but with greatly improved mechanical properties.(12) Recent data suggest that this material, because of good electrical, thermal, and tribological properties, may be a suitable sliding contact material for next-generation pulsed power generators. Figure 5 shows a typical copper-graphite HPC compact.

Molybdenum Alloys

The amorphous PM alloy NiMoFeB (METGLAS 7025™) has been studied using HPC. Although in the bulk of the finished compact (approximately 4.5 cm diameter by 1 cm length) amorphosity was not conserved, a highly dense microcrystalline

Figure 4. Aluminum HPC Compact

Figure 5. Copper-Graphite HPC Compact

4001.0094

structure was produced. This structure represents a new room-temperature metastable phase, named the η -Boride phase, which had not been observed in this alloy previously.(13) Such a compact is shown in figure 6. Another alloy of tungsten, zirconium, and molybdenum, (TZM PREP) was investigated. In the coarse, oxidized form, this PM product has proven difficult to consolidate by conventional means. After HPC, without special process control, this alloy shows very good density and a stable μ -phase

Figure 6. METGLAS 7025™ HPC Compact

Tungsten Alloys

HPC compacts of tungsten with nickel, cobalt, copper, or niobium alloying elements have been produced with good density and other properties.(2) However, pure tungsten is difficult to consolidate because of adverse die interactions at the very high temperatures and pressures required for the sintering reaction (approximately 3000C and 300 MPa). Furthermore, aggregation of powder particles below approximately 100 m size can result in non-uniform density and degraded mechanical properties of the compact. In addition, sintering of tungsten to near-theoretical density by conventional means requires hours in controlled atmospheres.(14) Recent data at CEM-UT suggests that a novel pre-processing technique for tungsten particles, combined with HPC, can result in very uniform tungsten parts of high density that have mechanical properties (specifically hardness) significantly higher than conventionally produced pure tungsten parts. Research is continuing into this application.

MANUFACTURING WITH HPC

Implementation of HPC into a manufacturing plant in the near term is feasible. The required power supplies and auxiliary equipment are commercially available, and the tooling and fixturing required are essentially designed from conventional mechanical, electronic, and hydraulic components.

Capabilities

Research results indicate that compact masses of 1.0 kg can be consolidated per 10 MJ of HPG capacity per operational cycle (one discharge per operational cycle). Industrially rated, actively cooled HPG's are available that can operate at full energy on a 5 min duty cycle.(15) To date, most HPC compacts have been cylindrical or disk coupons for research analysis. These are produced in ceramic lined, quick release diesets (figure 7) that are approximately 2.5 times the diameter of the finished compact. It is anticipated that prismatic, or constant section, shapes can be formed by HPC with special tooling design. Thus near-net shapes, such as turbine bladeforms, are probably feasible. Furthermore, consolidated PM parts can be joined to monolithic parts during consolidation. Figure 8 shows a copper disk bonded to an HPC-produced tungsten-iron alloy.

Cost and Productivity

On a per Joule basis, iron core HPG's represent the most economical reusable energy storage and pulsed power supply available. Capacitor banks, for example, are more costly by a factor of 5-10, while occupying as much as 10-100 times the volume, for an equivalent stored energy.

Figure 7. Quick Release HPC Dieset

Figure 8. Copper-Tungsten Alloy HPC Joint

Operational costs for HPG's are also low. Motoring to speed is accomplished at modest power levels (200-500 kW); auxiliary power requirements may total to an equivalent number. Total energy cost per cycle for a 10 MJ unit might therefore approach \$0.10, depending on local utility rates. Furthermore, because the high power discharge is accomplished off-line, no demand rates for high power surges are incurred.

CONCLUSIONS

The Center for Electromechanics at The University of Texas at Austin has applied pulsed iron core homopolar generators to a rapid, single residency process for compacting, sintering, and consolidating powder metal alloys and composites. Many materials, from lightweight to refractory alloys, can be consolidated with this process with high density and excellent properties. Consolidation time is very short compared to conventional powder metal processing techniques. Near-net shapes can be consolidated, and joints between consolidated and monolithic parts can be accomplished. Homopolar generators are economical, reliable, and inexpensive to operate.

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