Pulsed Magnetic Flux Compression Power Supplies for Hypervelocity Powder Deposition

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Abstract

After reviewing the process of hypervelocity plasma deposition using augmented railgun technology, the paper presents several new concepts of pulsed rotating electric generators designed to power, on an almost continuous basis, the laboratory system designed and built at The University of Texas Center for Electromechanics (UT-CEM), which successfully validated the method and conducted proof-of-principle experiments.

The two different rotating, repetitive pulsed power supplies described in the paper are: (1) an actively compensated flux compressor-alternator (actively compensated compulsator) and (2) a dc machine with series excitation, which so far did not have any application as a generator but proves, due to its self-excitation particularities, to be an almost ideal power source for the railgun.

It needs to be emphasized that the augmented railgun and the actively and passively compensated compulsators represent almost mature technologies due to the continuous development of electromagnetic launch technology by the U.S. Department of Defense and especially by the U.S. Army – ready to be applied to many advanced civilian applications as it is the case with the hypervelocity powder railgun accelerators for surface conversion.

Background: Hypervelocity Powder Deposition Using Railgun Technology

The success of the research described in this paper is based on two classes of concepts which only in combination can bring fundamental advances to both manufacturing and materials technologies.

The first class of concepts refers to the electromagnetic powder deposition (EPD) processes developed at The University of Texas Center for Electromechanics (UT-CEM) using the railgun technology to achieve hypervelocity powder spray in conjunction with plasma "snow-plow" with the promise of substantially improving both coating density and bond strength in surface conversion [1].

The second class of concepts refers to different original concepts of rotating, pulsed power supplies capable of transforming the EPD process from a very few shots event into a highly repetitive, almost continuous process of powder deposition and surface conversion [2,3]. Demonstrated energy and power levels have led us to pulsed electrical machines with kinetic energy storage as a superior choice. Also, there is an ideal match (magnetic flux compression – magnetic flux expansion) between the repetitive rotating power supplies of compulsator types and the augmented railgun accelerator [4,5,6].

Regarding the first class of concepts (EDP process), very significant results [1,7,9] have come from the research to date. For example, a comparison between Figs. 1 and 2 shows that the impressive particle velocity that EPS produces, leads to a denser coating than can be produced by existing coating methods. The reduction in the porosity of the coating will increase the corrosion resistance. The second result is seen by comparing Figs. 3 and 4 which depict, respectively, an EPD coating of chrome and a similar coating produced by electroplating. Preliminary results indicate that EPD may not only be a replacement for chrome plating, but it may also outperform this technology by the elimination of micro-cracks in the coating.

Viscous drag forces generated by high speed gas flow is the most efficient way to accelerate powder to high velocity [8]. What is required is a means of generating short bursts of high speed gas at a high repetition rate (to 30 Hz).

The EPD approach is a process which achieves high velocity gas flow by combining two technologies which have been developed at UT-CEM - pulsed power electrical energy sources and acceleration using the electromagnetic railgun force. Used with the snowplow process, these bursts then accelerate powder to speed in excess of 2 km/s. The gas minimally heats the powder. To prevent oxide formation of plating material, inert gas such as argon is used. Fig. 6 shows a schematic of the concept; key components necessary for an operating system are identified.

The EPD sprayer is actually an augmented railgun. The bore is filled with an ionizable gas, and a radio frequency (rf) excited cavity at the breech of the accelerator provides a line source of plasma [1]. A high energy electrical pulse, provided by a pulsed energy source, expands the line source into a planar arc which is driven forward by electromagnetic forces. The arc is an efficient snowplow sweeping the gas in the bore to a final velocity approximately twice the desired powder velocity. This shocked gas passes over a powder cloud introduced near the end of the gun and accelerates the powder through drag forces. The electrical and powder discharge frequency can be adjusted so that the deposition rate and thermal input to the substrate can be controlled. It can be shown [1,2,7,8] that current requirements are related to gas velocity by the relation

$$I = 16 V_{gas} \sqrt{\frac{\rho_{gas} A}{L'}}$$

where the current I is in kA and gas velocity V_{gas} is in km/s. The other quantities entering the equation are:

ρ_{gas} = the relative density of ambient gas being snowplow accelerated to velocity V_{gas}, with unit relative density corresponding to air at STP

A = the cross-sectional area (in cm^2) of the railgun

L' = the inductance per unit length (in μH/m) of the railgun structure

For example, using argon gas at STP (ρ = 1.389 times air) in a 1.6 cm^2 gun structure with inductive gradient 0.5 μH/m, to achieve a velocity of 5 km/s requires 135 kA driving current.

The electrical pulse width required is dependent on the fraction f of gas velocity to which the powder particle is to be accelerated. A practical value is 50% (f = 0.5). The pulse length is then given by the relation

$$\delta t = \frac{4}{3} \frac{\rho_{powder}}{\rho_{gas}} \frac{D_{powder}}{V_{gas}} \left(\frac{f}{1-f} \right)$$

where in addition to the previously defined quantities, we also have

δt = the electrical pulse duration in microseconds

ρ_{powder} = the powder density relative to air at STP

D_{powder} the effective diameter of the powder particles in microns

For reference, using 100 micron Inconel® powder yields pulse lengths of 100 μs.

Rotating, Repetitive Power Supplies

We are outlining the features of an original rotating machine, a flux compressor-compulsator-which can efficiently provide 100 μs pulse width, high current, pulse-shaped, one shot every 30 μs, approximately 100 million shots per year. The continuous power of the machine is 250 kW with a pulsed power rating of 80,000 kW supplied by rapid electromechanical energy conversion of the energy stored kinetically. Fast pulses have been extracted and demonstrated from rotary flux compressors [4,5,6]. Fig. 7 shows very schematically the capability of the compensated pulsed alternator-flux compressor to deliver large amounts of peak power in hundredths of microseconds.

Fig. 8 illustrates, as an example, the waveforms for the first compulsator-flux compressor designed and built to power a load of 96 flashlamp circuits used for a laser system. Approximately 2.5 MJ of energy and 7,500 MW required by the circuit by the time the current fell to the half-peak value, the half-width of the pulse being 0.325 ms. Fig. 9 shows a simplified circuit for simulations and Fig. 10 the four-poles compulsator performance.

Unlike the simplistic principle above, the compulsators in use, have a very complex construction, generalizing and exploiting the principle outlined in a refined and developed manner. In our case, the novel concept of the proposed electrical machine owes the precision of its output characteristics to an original way of controlling the magnetic flux locally in a piece-wise manner on both rotors and stators. The winding conductors, stranded and transposed in order to limit the transient field diffusion, are split in elements forming cells and segments, each element being connected in series with fast commutated power electronics devices as IGBTs. Such cells replace the traditional compulsator windings performing the flux compression, by transforming them in windings with variable structure on both rotors and stators controlling (by delay or advance) the flux compression process, thus controlling and synthesizing very precisely the powerful current pulse at each few microseconds interval. The global 80 MW pulse is precisely shaped by local commutation of the cells and segments.

Probably a place where the self-excitation in context of EML technology may be used with spectacular results, is the dc series generator, a machine which has no applications in everyday technology, but can serve as the ideal power supply for the augmented railgun used successfully as a hypervelocity plasma sprayer.

The dc series generator, due to its self-excitation particularities, represents a power supply, matching extremely well the characteristics demanded by the hypervelocity augmented railgun plasma accelerator. Closing the generator armature on the practical short-circuit of the railgun starts and leads to self-excitation.

For such a generator, the no-load characteristic must be calculated as for the separately excited machine, since at no-load, the excitation winding (in series) does not have current. The emf induced in the armature is found with the normal tools and procedures known from the classical electrical machine theory. In this kind of generator (series excitation - self-excited) to every point of the no-load characteristics corresponds a uniquely defined load current flowing through both excitation and armature windings. Fig. 11 shows a connection which will be used in powering the railgun plasma spray device. The self-excitation of both series generators connected parallel is balanced by placing each excitation winding in the armature circuit of the other generator.

Motoring up the generator is done as, of course, a series motor having the advantage of outstanding characteristics of such a drive at an almost ($T\omega$ = constant) constant power. An asynchronous generator, pulsed, repetitive and having a novel method of self-excitation was also proposed in the course of this project; however, it was developed only to a preliminary conceptual design phase.

Next Step

The next step for this research tries to complete the path from a promising experiment to a continuous base, electromagnetic powder spray process. The demonstration of the novel concept of electrical machine-magnetic flux compressor as the continuous-duty power supply for the process represents the necessary element for such a path completion. The requirements for the power supply mentioned of 80,000 kW pulsed power, 250 kW continuous, came from the energy per pulse of 4.3 kJ (kinetic energy of the compressed gas and powder 1.18 kJ, resistive energy 2.25 kJ, rail resistive energy 0.87 kJ) in 150,000 A pulses of 100 s with 25 s rise time, one pulse every 30 ms, 100 million shots per year.

The methodology of the research is taking advantage of a large library of data and the experience of six already built compulsators which have demonstrated [2,4,6,10] with a large safety margin all the global mechanical, electromagnetic, and thermal characteristics of the machine. (The last one, the CCEMG compulsator very recently built, has demonstrated 2,500 MW as compared with 80 MW pulsed power required for the proposed concept of 460 m/s peripheral velocity as compared with 340 m/s for the flux compressor.) The proposed power supply concept will transform the "compulsator" technology from a very high power pulse approach to the more complex and refined approach in which the power remains large, but is "ideally" controlled by a synthesis process of the variable structure cells achieving the magnetic compression locally and by a subtle strategy microprocessor implemented.

A pulsed transformer will be embedded in the machine, filtering the unwanted output and, by its characteristics, assuring a sudden drop of the current to zero at the end of the shot, thus reclaiming the magnetic energy from the railgun accelerator, and the optimal ending of the pulse.

Summary

This paper describes a novel hypervelocity power deposition process already proven by proof of principle experiments and a new rotating, pulsed, electrical machine of "active compulsator type" which will make the process highly repeatable, almost continuous. An alternative to such a machine is a special self-excited dc series-excited generator.

Acknowledgement

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Fig. 1. EDP buildup coating

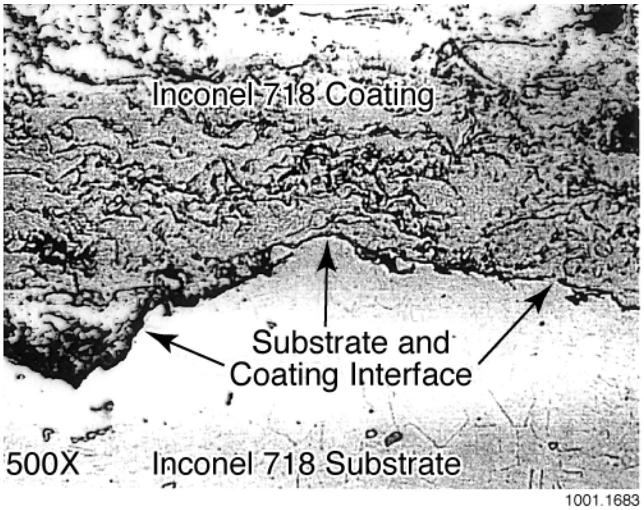

Fig. 2. Coating produced by the high velocity oxygen fuel method

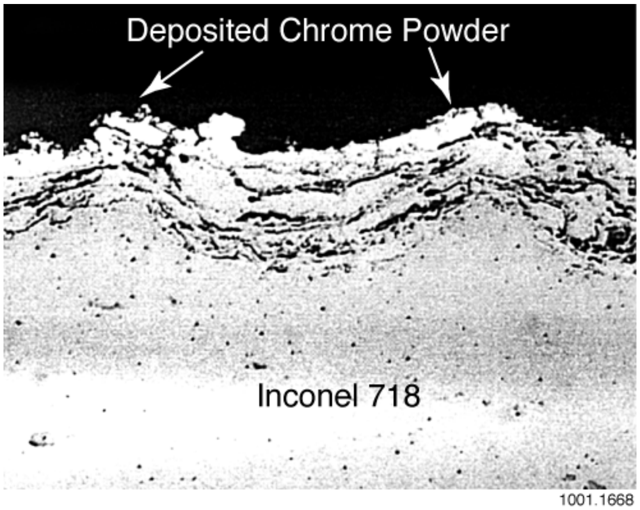

Fig. 3. EDP chrome coating

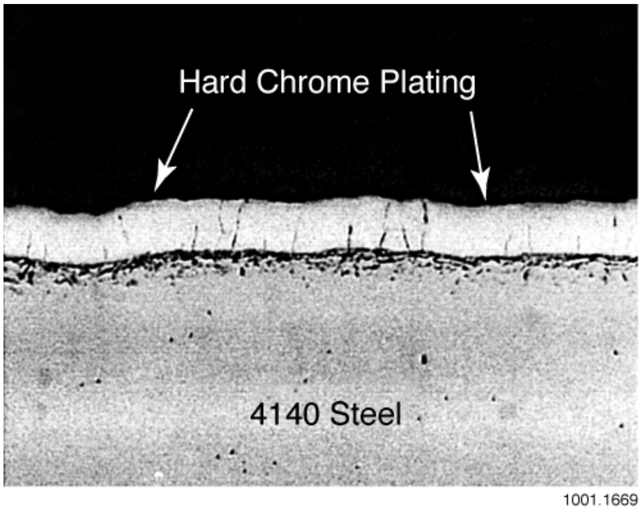

Fig. 4. Chrome plating

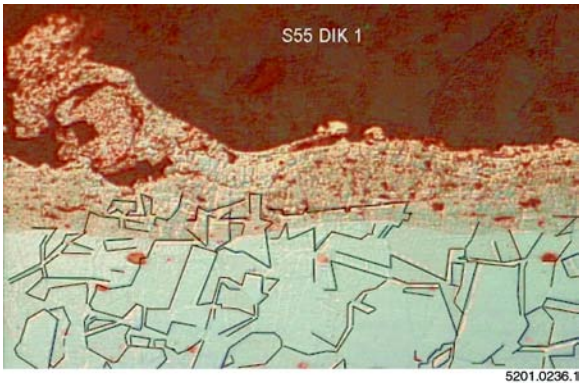

Fig. 5. Highlighted examples of grain growth across substrate coating interface

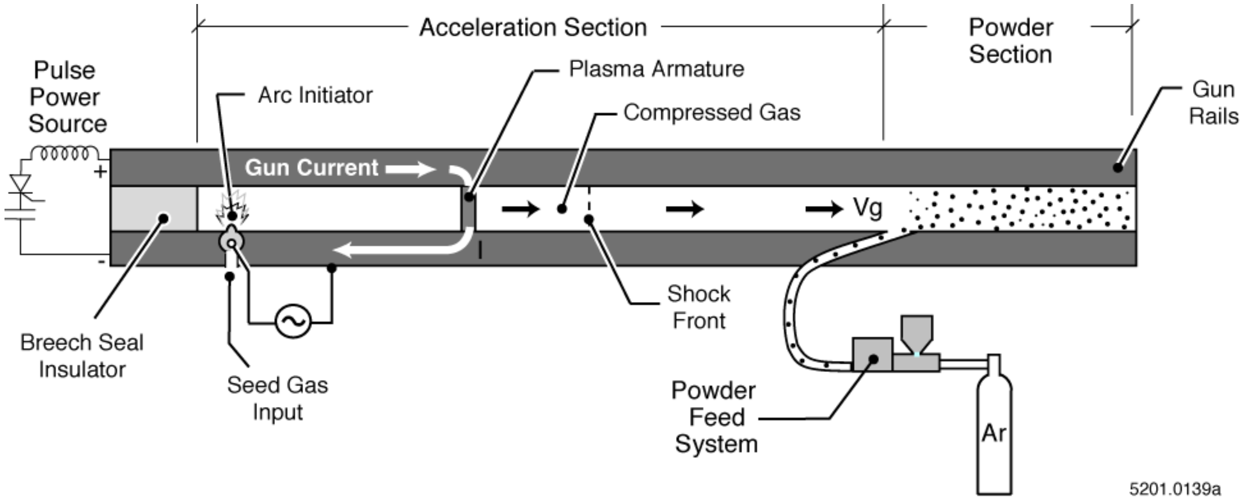

Fig. 6. Schematic showing EPD system components

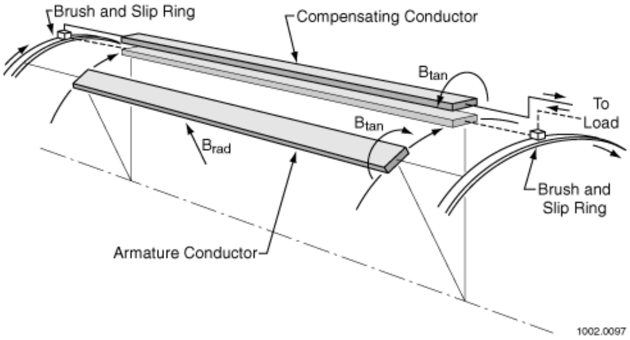

Fig. 7. A single armature conductor rotating toward a single compensating conductor. The radial B-field, produced by the stator windings, induces a current in the moving armature conductor which flows through the slip rings and brushes to the load and, subsequently, through the compensating conductor, as shown. As the two conductors are forced together, the compression of the combined fields increases the flux density in the region between them.

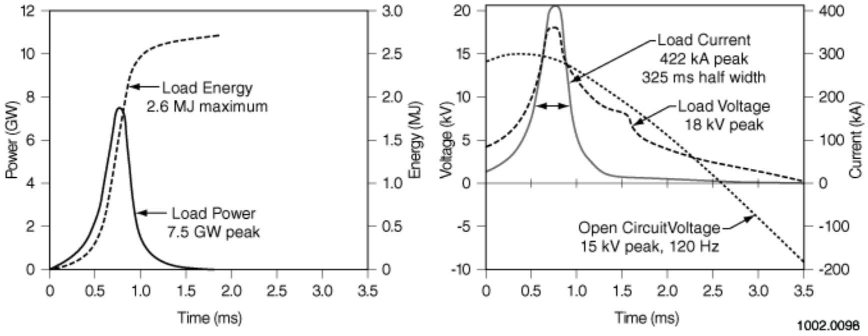

Fig. 8. Waveforms for a special case to the first compulsator-flux compressor designed to power a load of 96 flashlamp circuits used for a laser system. Approximately 2.5 MJ of energy were to be delivered to the circuit by the time the current fell to the half-peak value. the lower curves are the dynamic voltage and current during the pulse and the open-circuit voltage when no trigger is fired. The dynamic voltage peaks are higher than the open circuit voltage because of the flux compression effect in the device.

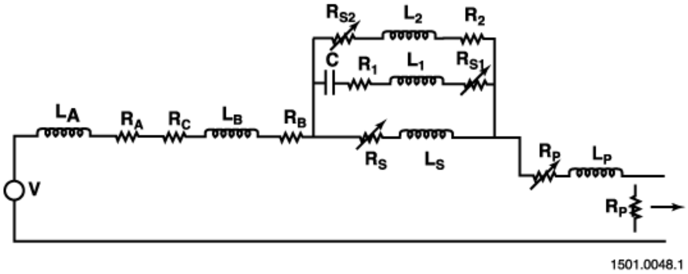

Fig. 9. Circuit for simulations

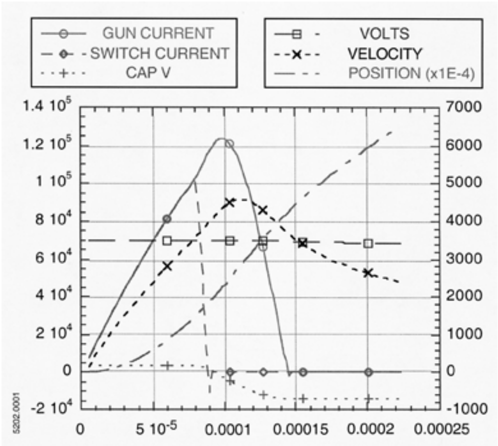

Fig. 10. Four-Pole compulsator circuit performance

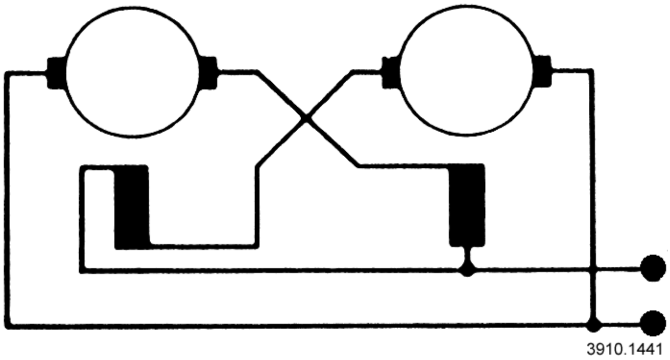

Fig. 11. Series excitation pair of DC machines for EML powder deposition