Hypervelocity Plasma Sprayer Using Railgun Accelerators

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Abstract—This paper describes hypervelocity plasma spraying with railgun systems and describes the laboratory system designed and built at The University of Texas at Austin, which successfully validated the method of hypervelocity plasma spraying and conducted proof of principle experiments for hypervelocity plasma-powder deposition, using a railgun system.

The bore of the railgun is filled with an ionizable gas, and a radio frequency-excited cavity provides a line source of plasma. Fast, high-energy electrical pulses from the magnetic flux compression device expand the plasma line into a planar arc driven by Lorentz forces. The arc is an efficient "snowplow" sweeping the gas to velocities of 4 to 5 km/s, which is twice the desired powder velocity producing coatings of superior quality in an almost continuous manner, compared to the existing plasma sprayers as shown by state-of-the-art Hadland CCD framing cameras. The paper mentions how the Rayleigh-Taylor instabilities are circumvented and the role and the interplay of the compensated current pulse shape of pulsed machines.

For a technology to be viable, the process must be driven on a continuous basis. Then the power source must be also an energy storage device capable of a large number of shots, repeated at a relatively high frequency. The process requires an average power of 250 kW, but in successive pulses of 100 ms duration at a peak power level of 80,000 kW. In order to operate without interruption, novel concepts of repetitive pulsed electrical machines were developed. One refers to an actively compensated compulsator – embedding a capacitive pulse forming network. The second is a pair of series-excited dc generators operating in tandem.

I. RESEARCH BACKGROUND

The research was based on several original concepts which, in combination, hold the promise of fundamental advances to both manufacturing and materials technologies. The first novel concept uses a hypervelocity accelerator for a new thermal spray process using electromagnetic forces to accelerate powder particles to velocities of 2 km/s or higher [1].

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At velocities in excess of 2 km/s, powder particles have sufficient kinetic energy to melt their own mass and an equivalent substrate mass on impact, thus creating a fusion bond of greater strength than created by the low velocity existing processes, as well as superior coating density and uniformity.

Proof of principle experiments have confirmed proper operation of the process by capturing photographs of powder particles in flight using state-of-the-art Hadland CCD framing cameras. The research is moving to operating the process to produce coatings on substrate in an almost continuous mode, requiring novel, repetitive, pulsed, and extremely powerful power supplies, with a high frequency operation, many times a second, day in and day out.

The other original concepts are such power supplies, among them a new electrical machine-flux compressor, pulsed with precisely controllable output capable of matching ideally the powder spraying hypervelocity accelerator at any moment of time.

While novel, a pulsed magnetic flux compressor-rotating electrical machine belongs, in a larger sense, to a family of electrical machines generically named compulsators invented at UT-CEM [1,2,3,4,5,6], six of them of very different types which were already built for the U.S. Departments of Defense and Energy. (The U.S. Army is pursuing vigorously the compulsator as the only alternative for power supply for electromagnetic guns, planned to be deployed in the year 2015 [6]).

Due to their compensation systems, the compulsators are low internal impedance machines designed for pulsed duty and capable of providing large current pulses, with a rapid rise time (in our case, less than 25 μ s to 80,000 kW-80 MW pulsed power) to a low impedance load—a hypervelocity square bore railgun accelerator (SBA).

The novelty of the proposed machine lies in advancing the use of compulsator and magnetic flux compression principles from the brute force of a pulsed discharge to the refined way of constructing electromagnetically the ideal current pulse shape for the process. In order to achieve this goal, the proposed machine's generic windings are split into cells and segments, each in series with power electronic devices (IGBTs), forming rotor and stator windings which change their structure during the flux compression.

A second novel, repetitive power supply is represented by a pair of series-excited DC generators operating in tandem, in which the generators' armatures are closed on the practical short circuit of the railgun which starts the self-excitation process. A third novel power supply was developed only to a preliminary conceptual design phase, and involves a self-excited, multi-pulsed, asynchronous generator.

Successful development of a production prototype will bring fundamental advances to manufacturing. This process can be used to build up material of parent material strength because of the potential to create a fusion bond with the substrate (Fig. 1). It can build up the material with less heat input than a welding process, therefore mitigating substrate warpage. The more energetic impact will create denser coatings. It can be used to apply chrome to substrates, therefore avoiding the generation of environmentally hazardous hexavalent chrome, a by-product of electroplating. Due to the improved bond strength, material buildup may be possible, allowing the formation of macrostructures.

II. PROCESS FUNDAMENTALS

The electromagnetic powder deposition (EPD) sprayer, a railgun, consists of two metallic rails with insulating sidewalls separating them. 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 [7]. A high-energy electrical pulse provided by the pulsed energy source (Fig. 2) expands the line source into a planar arc which is driven forward by electromagnetic forces. Fig. 2 shows a simple railgun and the electrical currents and magnetic fields which interact to create the Lorentz force (the cross product of the current density vector and the magnetic field vector). The arc is an efficient snowplow [8], sweeping the gas in the bore to a final velocity approximately twice 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. Considerations of the snowplow mechanism drive by electromagnetic Lorentz railgun forces [9] show that current requirements are related to gas velocity by the relation:

$$I = 16 V_{\text{gas}} \sqrt{\frac{\rho_{\text{gas}} A}{L}} \quad (1)$$

where the current, I , is in kA, the gas velocity, V_{gas} , is in km/s, ρ_{gas} is the relative density of ambient gas being snowplow accelerated, A is the cross-sectional area, in cm^2 and L is the inductance of the railgun structure per unit length, in $\mu\text{H}/\text{m}$. For example, using argon at STP ($r = 1,389$ times the air value) in a 1.6 cm^2 gun structure with

Fig. 1. Fusion bond substrate

Fig. 2. The plasma armature is accelerated down the length of the railgun by an electromagnetic Lorentz force generated by the interaction of the magnetic field surrounding the rails and the current flowing through the armature

inductive gradient $0.5 \mu\text{H}/\text{m}$, to achieve a velocity of 4 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:

$$\delta t = \frac{4 \rho_{\text{powder}} D_{\text{powder}}}{3 \rho_{\text{gas}} V_{\text{gas}}} \left(\frac{f}{1-f} \right) \quad (2)$$

where δt is the electrical pulse duration in microseconds, ρ_{powder} is the density relative to air at STP; and D_{powder} is the effective diameter of the powder particles in microns. For reference, using 100 micron Inconel powder yields pulse lengths of about $100 \mu\text{s}$. To avoid plasma Rayleigh-Taylor instabilities, the power source must provide current to the square bore accelerator (SBA) with a rapid rise time ($25 \mu\text{s}$). The ideal current pulse would jump instantly to 150 kA , remain constant for about $100 \mu\text{s}$, and drop instantly to 0 kA . For laboratory testing, a stage PFN with current waveform (Fig. 3) has been used as a power source.

For the technology to be viable, the process must be driven on a continuous basis. Then the power source must be also an energy storage device capable of multiple shots. Demonstrated energy storage levels listed in [3], in J/m^3 , as 9.1×10^6 for electric field (capacitors) 1×10^8 for magnetic field (inductors) as compared to 1.2×10^9 for kinetic energy storage (rotating machines), lead us to the electrical machines as a superior choice. However, the $100 \mu\text{s}$ pulse width eliminates the ordinary electrical machines from competition due to their extremely low pole pitch.

III. ROTATING, REPETITIVE POWER SUPPLIES

We are outlining the features of an original rotating machine, a flux compressor-compulsator-which can efficiently provide $100 \mu\text{s}$ pulse width, high current, pulse-shaped, one shot every $30 \mu\text{s}$, approximately 100 million shots per year. The continuous power of the machine is 250 kW with a pulsed power rating of $80,000 \text{ kW}$ supplied by rapid electromechanical energy conversion of the energy stored kinetically. Fast pulses have been extracted and demonstrated from rotary flux compressors [6,7]. Fig. 4 shows very schematically the capability of the compensated pulsed alternator-flux compressor to deliver large amounts of peak power in less than 1 ms .

Fig. 5 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. 6 shows a simplified circuit for simulations and Fig. 7 the four-poles compulsator performance

Unlike the simplistic principle above, the compulsators in use have a very complex construction, generalizing and exploiting the above principle 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.

Fig. 3. Gun current generated by the PFN circuit. The peak current and duration are dictated by required powder velocity

Fig. 4. 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. 5. 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

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 an ideal 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.

IV. A CONTINUOUS HYPERVELOCITY PLASMA SPRAY PROCESS

Figs. 8 through 11 show the superiority of the proposed hypervelocity plasma sprayer in comparison to existing state-of-the-art technologies.

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 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.

V. 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.

Figure 6. Circuit for simulations

Fig. 7. Four-pole compulsator circuit performance

Fig. 8. EPD Build-up coating (compare with Fig. 9)

Fig. 9. Coating produced with the high velocity oxygen fuel method (compare with Fig. 8)

Fig. 11. Chrome plating produced with electroplating (compare with Fig. 10)

Fig. 10. Chrome coating produced with EPD (compare with Fig. 11)

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