Multi-Shot Power Supply Using Capacitors for an Electromagnetic Powder Deposition (EPD) Gun

By:

D.G. Davis
J.L. Bacon
R.L. Sledge
R.J. Polizzi
R.C. Zowarka
J. Uglum

11th IEEE International Pulsed Power Conference
Baltimore, Maryland
June 29-July 2, 1997

PN - 235

Center for Electromechanics
The University of Texas at Austin
PRC, Mail Code R7000
Austin, TX 78712
(512) 471-4496

MULTI-SHOT POWER SUPPLY USING CAPACITORS FOR AN ELECTROMAGNETIC POWDER DEPOSITION (EPD) GUN

Darwin Davis, James Bacon, Robert Sledge, Robert Polizzi, Raymond Zowarka, John Uglum
Center for Electromechanics
The University of Texas at Austin
PRC, Mail Code R7000
Austin, TX 78712

Abstract

The Department of Defense (DoD) and commercial entities are dependent on chemical plating and coating processes to replace worn or eroded material on damaged parts. Air Force Logistics Centers have been forced to consider replacement methods for repair operations due to the tightening of government regulations on the use of toxic and hazardous materials.

The electromagnetic coating process is a viable alternative to existing build-up methods, and is based on proven "railgun" technology. Railguns have been under development for 15 years by the DoD and are high energy capacity electrical systems designed for rapid acceleration of an object. Railguns are effective in accelerating projectiles to very high, armor piercing velocities exceeding 2 km/s. Current thermal spray technology limits coating velocities to the 1 km/s range. In the electromagnetic coating process, equipment similar to a railgun accelerates the coating material. The impressive acceleration capability of electromagnetic systems is expected to produce coatings with superior density and bond strength properties. In addition to potentially improving coating properties, the electromagnetic coating process may serve as a replacement for operations that generate hazardous chemical wastes, such as hard chrome plating. The purpose of the program is to identify, develop, and design a production system for high quality coatings in industrial manufacturing and repair operations.

EPD PROCESS SUMMARY

The EPD process converts pulsed electrical energy into kinetic and thermal energy in order to accelerate and heat powder material to conditions suitable for deposition. A high pressure plasma armature is electromagnetically accelerated using a railgun. A supersonic pressure wave is created when the armature accelerates through and "snowplows" the ambient quantity of gas ahead of it. The gas column is heated, compressed, and accelerated to the entrainment section of the gun, where some of the thermal and kinetic energy is transferred to an injected stream of powder material. The acceleration burst is repeated rapidly to supply the required deposition rate and to maintain steady thermal conditions.

The EPD gun's rate of repetition is determined by the required deposition mass. To be competitive with existing processes we have selected to accelerate 24 grams per minute, or 0.4 grams per second. We can accelerate 13 milligrams of powder per shot, therefore the rep rate must be 30 Hz. We are ultimately interested in steady state operation, but we designed this power supply for proof of principle, and with economic considerations in mind. The goal is to provide enough discharges to approach steady state operating conditions, up to 100 discharges.

Existing state of the art thermal spray processes (HVOF, D-Gun, Plasma Spraying) are limited to powder velocities of about 1 km/sec because they rely on the thermodynamic expansion of gases. This new thermal spray process using electromagnetic forces can accelerate powder particles to a final velocity of up to 2 km/sec. At this velocity powder particles have sufficient kinetic energy to melt their own mass and an equivalent substrate mass on impact. This interaction provides the potential for forming a fusion bond between

the deposited material and the substrate. The acceleration capability of electromagnetic systems is expected to produce coatings with superior density and bond strength properties.

POWER SUPPLY SUMMARY

Figure 1. System Block Diagram.

The system under development at the Center for Electromechanics will provide 10 discharges at a 30 Hz rate. **Figure 1** shows the basic components of the EPD system. A Pulse Forming Network (PFN), which is a capacitor bank designed to provide a specific current profile, provides electrical energy to a square bore accelerator (SBA), or railgun. The railgun is filled with argon at atmospheric pressure and near its breech is a Radio Frequency (RF) arc initiator. Powder is fed into the last 1/3 of the SBA through two injection ports. When the Triggered Vacuum Switch (TVS) is closed the PFN discharges into the SBA, driving a plasma armature down the length of the railgun. As mentioned earlier, the plasma pushes a column of gas in front of it at supersonic speed. The shocked column of gas increases in length as more and more argon gas is swept up. This process of pushing a shocked column of argon gas is referred to as snowplowing.¹ The snowplow action has been simulated and experimentally verified.²

Once the PFN has discharged, the TVS opens. The PFN must then be recharged by the recharge capacitor. This is accomplished in a two step process. First, the Insulated Gate Bipolar Transistor (IGBT) switch is closed and current flow is initiated through the charging inductor. The current through the inductor builds to a predetermined level such that the inductor stores sufficient electrical energy to recharge the PFN. Next, the Silicon Controlled Rectifier (SCR) switch is closed and the IGBT switch is opened. The current flowing through the inductor is diverted into the PFN, and the PFN is recharged. The SCR switch passively opens when the charging current goes from positive to negative. The TVS switch is closed and the cycle is repeated.

The IGBT switch, the SCR switch and the TVS switch each have their own control blocks. The switch blocks provide gate signals when commanded by the controller block. Each block is galvanically isolated and communicated with only through fiber optics. This insures no ground loops, which could introduce noise in the presence of high transient electromagnetic fields. A sensor block monitors the health of the system and shuts the system down if a fault is detected. The worst case would be if the IGBT switch didn't open and the six high powered IGBTs were exposed to excessive current. To prevent this, the sensor block looks for an over current condition and can send a signal to the explosive opening switch causing it to explode, which physically opens the circuit. This is a safety feature which hopefully will be rarely used during the operation of the system.

CONTROLLER

The control circuit operation during discharges is a major concern due to the high level of electrostatic and electromagnetic field (EMF) noise present during a railgun discharge. The Radio Frequency (RF) arc initiator will also be a possible noise source. With this noisy environment, the requirement for total fiber optic communication was necessary. The IGBT, SCR, and TVS switches are triggered by fiber optic pulses from the controller block. However, in order to trigger these components, their respective control circuitry must be fiber optically enabled by the sensor block. When the sensor block senses a fault condition the enables are removed, and this prevents further trigger signals from being accepted by the control circuitry. Comparators are used to sense fault conditions for current and voltage. When the sensor block senses an over current condition, the explosive opening switch shown in Figure 1 will be blown to open the circuit so the IGBTs won't try to conduct excessive current. The recharge capacitor bank contains enough energy to reach currents much higher than the IGBTs are able to conduct. The control circuitry for each block is powered by a motor-alternator set. This allows each switch control block to be isolated from the experiment and the ground plane potential to float during switching. Within the IGBT and SCR switch control blocks, a further level of isolation is required. The IGBTs and SCRs are put in series to increase the voltage holdoff capability, however, during holdoff each IGBT and SCR are at different voltages. These differences are in the kilovolt range, whereas the trigger circuitry operates in the 20 volt range. Since the control circuitry must be able to float to the voltage level of it's switch, lithium batteries are used to power only the components associated with triggering it's respective IGBT or SCR. The switch trigger circuitry is isolated from the rest of the control circuitry by optocouplers. The optocouplers were AC and DC hipotted to double the voltage they are expected to experience during operation.

A coaxial arrangement had to be maintained throughout the power supply to avoid EMI noise as much as possible. The control circuitry along with the switches are contained within shielded metal boxes. The IGBT and SCR switches are contained within a second shielded box, which serves to protect the control circuitry from noise created by IGBT and SCR switching. Waveguides were used for all penetrations into each box.⁵ Penetrations were necessary for fiber optics, circuit power, TVS trigger cable, and the current carrying conductors for the IGBTs and SCRs. The two inner boxes, which house the IGBTs in the IGBT switch block and the SCRs in the SCR switch block, are used to conduct current. In this coaxial arrangement the current conducts through the IGBT or SCR switches in one direction, and the return path is through the box containing the IGBT or SCR. This keeps the electromagnetic fields contained within the box, thereby, reducing the chance to introduce noise in the control circuitry.

GUN CIRCUIT

Figure 2 shows the gun circuit components. The PFN consists of four 800 microFarad capacitors in parallel. To obtain the current shown in Figure 3, the PFN must be charged to four kilovolts. Due to plasma instability considerations, the PFN resistances

Figure 2. Gun Circuit.

Figure 3. Gun Current.

and inductances must be tailored to the values modeled.² This includes the PFN buswork and the internal inductance and resistance of the PFN capacitors. Six TVS-40 25kV, 140kA, Triggered Vacuum Switches (TVS's) will be used to switch the PFN into the Square Bore Accelerator. A Radio Frequency (RF) arc starter will be used to supply the plasma needed during the 20 microsecond risetime.⁴ The plasma source will run continuously, except for when it goes out briefly during a discharge. The plasma source must be ready for a discharge every 30 milliseconds. Six TVS's are used in parallel for turn off when current goes through zero. A single TVS could carry the current, however, tests performed at CEM-UT have shown that the TVS's will reliably turn off a current di/dt of 600 amps per microsecond. Simulated di/dt at turn off is approximately 2800 amps per microsecond. Therefore, six TVS's should turn off 3600 amps per microsecond, assuming the TVS's share current properly. Current sharing tests were also performed and confirmed proper operation.

RECHARGE CIRCUIT

Figure 4. Recharge Circuit.

Figure 5. Inductor, IGBT, and SCR Current.

Figure 6. Recharge Cap and PFN Volts.

Figure 7. IGBT and SCR Switch Volts.

Figure 4 shows the recharge circuit. Six EUPEC FZ800R33KF1 3300V, 800A IGBTs are used to switch current from the recharge capacitor bank through the inductor. At a preset current level the three SPCO XSPT402BHT 5000V, 4500A SCRs are switched on, the IGBTs are switched off, and current commutates from the IGBT into the PFN. Figure 5 shows the modeled inductor, IGBT switch, and SCR switch currents. The rising portion of the inductor current is carried by the IGBTs. The falling portion of the inductor current is carried by the SCRs. The IGBT current rises to a peak current of 1200 amps. The six IGBTs in series are rated for an average current of 800 amps, they are capable of switching a maximum pulse current of 1600 amps. The inductor carrying 1200 amps will supply enough energy to charge the PFN to 3400 volts. When 1200 amps is sensed by the control system, the IGBTs are all commanded to open and the SCR's trigger signal is sent. However, current cannot conduct in the SCRs until the IGBTs are turn off. In fact, the IGBT switch turn off di/dt equals the SCR switch turn on di/dt . While current is conducting through the SCR, the PFN is being charged. Figure 6 shows the PFN and the recharge capacitor voltages. Figure 7 shows the IGBT and SCR switch voltages. Each IGBT is rated for 3300 volts, which is a total holdoff capability of 19.8 kilovolts. Each SCR is rated for

5000 volts, which is a total holdoff of 15 kilovolts. Simulation indicates 9 kilovolts of holdoff are required for the IGBTs and 5 kilovolts for the SCRs, giving a safety factor of over 100% for the IGBTs and 150% for the SCRs. The recharge bank is made up of seven 4000 microfarad capacitors. This system is designed for ten discharges with the option to add more capacitance for more discharges in the future, if necessary. The charging inductor is 30 millihenries and is a spool of wound cable.

Figure 8. Subscale Modeled Currents.

Figure 9. Subscale Experimental Currents.

A subscale test was designed to perform laboratory tests using one IGBT and one SCR in the same switching arrangement as shown in **Figure 4**. The subscale tests were designed for two reasons: to determine whether the switching arrangement was feasible and to determine whether the model correctly predicted system parameters such as voltages and currents. **Figures 8 and 9** show the modeled versus the experimental waveforms.

IGBT AND SCR TRIGGERING

IGBT switching and triggering was a major concern, since less was known about them compared to triggering SCRs. Two major IGBT switching concerns are transient voltage spikes created and voltage sharing during switching, both of which can be controlled with a gate resistor in series with the intrinsic capacitance of the IGBT gate trigger. Without a gate resistor the IGBT would turn off in 0.2 microseconds. This turn off time, coupled with the circuit inductance, would create voltage spikes much higher than the IGBT's voltage rating. A gate resistor is used to increase the switching time from 0.2 to 10 microseconds, so as not to destroy the IGBTs and SCRs. The resistance can be increased more if dictated by higher circuit inductances. **Figure 10** shows the IGBT current and voltage waveforms modeled with a 2 microsecond switching time and **Figure 11** shows the same waveforms but with a 10 microsecond switching time. In this case, increasing the

Figure 10. 2 Microsecond Switching Time.

Figure 11. 10 Microsecond Switching Time.

switching time eliminated the transient voltage spike. Voltage sharing can be controlled by assuring that the gate resistances are set to charge and drain the intrinsic gate capacitances at the same rate. This is true for series and parallel operation, except in parallel operation current sharing is being controlled.

The SCR trigger signal is sent when the IGBT is commanded to turn off. However, due to the gate resistance which was introduced, it takes approximately 200 microseconds from when the IGBT is commanded off to when the current drops from 1200 amps to zero. The 200 microsecond delay is caused by the time required for the gate voltage to discharge down to the gate threshold voltage. The threshold voltage is the voltage at which the IGBT switches from low impedance to high impedance (over a 10 μ s interval), or vice versa. A 200 amp gate pulse is supplied to the SCRs for 500 microseconds, allowing the IGBTs time to switch. The SCR trigger is also shown in **Figure 9**. Large electrolytic capacitors are used to supply the energy necessary to perform ten shots without having to recharge. Smaller IGBTs are used to switch the SCR's trigger current. Snubber resistors and capacitors are used to control voltage spikes created by the SCR.

DIAGNOSTICS

The PFN and recharge bank voltages are monitored for over voltage and the PFN will be checked for proper discharge. For instance, if the PFN was properly charged to 3000 volts and it did not go below a voltage of 2000 volts, it probably didn't discharge and should not be recharged again because it would increase the voltage already present to a voltage level higher than the PFN capacitor rating. Two Nicolet Pro Series, the Pro 90 and the Pro 40, oscilloscopes are used to record data. To measure these voltages two 1000:1 Tektronix probes are used with two Nicolet 3000 ISOBE fiber optic isolators. The receiver end of the ISOBEs are located in the sensor block, which senses fault conditions and prevents continued discharges by removing the enables from all the control circuitry. A Pearson coil along with an ISOBE is used to monitor the inductor current. The inductor current is monitored for two reasons; to sense over current and to trigger the IGBT when 1200 amps are reached. Because the recharge bank has dropped to some value lower than the previous discharge, it takes slightly longer on each discharge to reach the specified level of 1200 amps.

CONCLUSION

A single discharge of powder on a substrate does not allow enough sample build up to evaluate coating quality. A rep rate power source for laboratory proof of principle testing was required. A PFN was selected as the pulse power source for its pulse shaping capabilities. The PFN is recharged using solid state controlled capacitor bank. The system is capable of 10 shots and expandable to 100 shots with the addition of capacitors. The 10 shot capability will supply the needed coating thickness and future expansion will allow exploration of coating dynamic processes related to multiple impacts.

REFERENCES

1. J.W. Shearer, "Xenon Shock Waves Driven by High Magnetic Fields", Proc. 2nd International Conf. On Megagauss Magnetic Fields, 1979.
2. J. Uglum, J. Bacon, D. Davis, R. Polizzi, B. Sledge, R. Zowarka, "Scaling Analysis of the Electromagnetic Powder Deposition Gun", United Thermal Spray Conference, September 1997.
3. J. Bacon, J. Uglum, D. Davis, R. Polizzi, B. Sledge, R. Zowarka, "The Diagnostic History of a New Electromagnetic Power Deposition System", United Thermal Spray Conference, September 1997.
4. B. Sledge, J. Bacon, J. Uglum, D. Davis, R. Polizzi, R. Zowarka, "Arc Initiation for the Electromagnetic Powder Deposition Gun", United Thermal Spray Conference, September 1997.
5. R. Morrison, "Grounding and Shielding Techniques in Instrumentation", John Wiley & Sons, Inc., 1967.