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Concept for Lightweight Spaced-Based Deposition Technology

Michael L. Fulton
Ion Beam Optics Inc.
Thousand Oaks, CA

André Anders
Lawrence Berkeley National Laboratory
Berkeley, CA 94720

Corresponding Author:
Michael Fulton, President
ION BEAM OPTICS Inc.
2060 E. Ave de Los Arboles #D243
Thousand Oaks, CA 91362-1376
805-277-9464
805-277-9477 (Fax)
mfulton@ionbeamoptics.com
www.ionbeamoptics.com

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Michael L. Fulton
Ion Beam Optics Inc.
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André Anders
Lawrence Berkeley National Laboratory
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ABSTRACT

In this contribution we will describe a technology path to very high quality coatings fabricated in the vacuum of space. To accomplish the ambitious goals set out in NASA's Lunar-Mars proposal, advanced thin-film deposition technology will be required. The ability to deposit thin-film coatings in the vacuum of lunar-space could be extremely valuable for executing this new space mission. Developing lightweight space-based deposition technology (goal: < 300 g, including power supply) will enable the future fabrication and repair of flexible large-area space antennae and fixed telescope mirrors for lunar-station observatories. Filtered Cathodic Arc (FCA) is a proven terrestrial energetic thin-film deposition technology that does not need any processing gas but is well suited for ultra-high vacuum operation. Recently, miniaturized cathodic arcs have already been developed and considered for space propulsion. It is proposed to combine miniaturized pulsed FCA technology and robotics to create a robust, enabling space-based deposition system for the fabrication, improvement, and repair of thin films, especially of silver and aluminum, on telescope mirrors and eventually on large area flexible substrates. Using miniature power supplies with inductive storage, the typical low-voltage supply systems used in space are adequate. It is shown that high-value, small area coatings are within the reach of existing technology, while medium and large area coatings are challenging in terms of lightweight technology and economics.

INTRODUCTION AND MOTIVATION

In this contribution we will describe a technology path to very high quality coatings produced in the vacuum of space, and in particular in the extreme vacuum on the lunar surface.

The quality of space vacuum varies in four different space environments prescribing limits on the implementation of space-based deposition technology.

Due to atomic oxygen fluence (on the order of 2.3 x 10^{20} atoms/cm^2) in Low Earth Orbit (LEO), the quality of the vacuum is not suitable for space-based depositions unless oxide films are desired. LEO vacuum can be enhanced by using a bow shock shield, a plate that is deployed at the front of a spacecraft that literally plows through the gas atoms, leaving a much cleaner vacuum in its path. This technique has been demonstrated on the Space Shuttle and proves that even LEO thin-film manufacturing could be possible.

High Earth Orbit (HEO) vacuum is at least an order of magnitude harder than LEO, but using the bow shock shield is not a useful option at those altitudes. Due to the difference between molecular and viscous flow in a vacuum, the random movement of gas atoms would migrate around the shield overcoming the ballistic plowing effect.

Lunar vacuum, however, is of extremely high quality, reading about 100 picoTorr during the day and 1 picoTorr at night. This is because solar wind and sunlight quickly remove most gas atoms within a period of from 15 minutes (for hydrogen and helium) and perhaps up to 100 days for heavier atoms [1]. The deposition processes will require tailoring to the specific space-vacuum environments.

Space-based thin-film deposition technology, when it becomes available, will be an integral part of our future space missions. For example, it will be enabling to fabricate, modify, repair, or enhance large area reflectors. Such reflectors serve to supply power to space facilities, or they can be part of thermal insulation and control structures, or imaging or communication systems. Upon returning to the moon, there will be a crucial need for all of these applications.

Large-area adaptive-optical space telescope mirrors could be robotically assembled on the far side of the Moon to replace the Hubble Space Telescope. Once in place the optical reflecting surface can be coated with a pure silver thin film that would not be subject to environmental degradation, as now seen on terrestrially produced films.

One of the most promising technologies for space-based thin-film deposition of silver is Filtered Cathodic Arc Deposition (FCAD), which has been shown to produce dense, extremely smooth, high-quality metal films by the energetic condensation process, which is a self-ion-assisted process.

Following upon the development of miniature vacuum arc thruster (VAT) technology for space propulsion [2], it is now in the realm of reality for an extremely light weight FCAD system to be designed and constructed, enabling the coating of small to medium, and eventually large substrate surfaces in the vacuum of space.

TERRESTIAL FILTERED CATHODIC ARC TECHNOLOGY

As described in the 2005 SVC publication [3], FCAD technology has been employed in the production of a variety of thin-film applications.

In the cathodic arc technology, the cathode material is the feedstock for the plasma and ultimately determines the composition of the coating. The solid is transferred to the plasma phase by rapid phase transition at cathode spots. The material briefly transitions through the vapor and liquid phases to become fully ionized plasma containing multiply charged ions. Ions are accelerated to supersonic velocity (with respect to the ion sound velocity) by the pressure gradient and the electron-ion coupling due to Coulomb interaction. Plasma charge state distributions and ion velocity distributions have been studied for practically all metals of the periodic table (e.g. [4, 5]).

Most terrestrial versions of the FCAD technology uses a continuously operating arc thus requiring intense water cooling of cathode and anode. Typically, a massive power supply is employed, often a conventional arc welding supply. Modern and compact switch-mode supplies are now available, however, at the typically 2-5 kW DC range, the weight of such supply is still 10 kg and greater. To stabilize the DC arc it is common to add some low pressure level of Ar (about 10^{-4} Torr) which helps to promote "perpetual" reignition of the short-lived cathodic arc spots.

Along with the plasma, undesired "macroparticles" are generated that need to be removed from the plasma to ensure a high quality of the coatings. Macroparticles are solidified debris particles produced at cathode spots. Their size is in the range 0.1-10 μm, with the smaller particles occurring much more frequently than the larger. In any case, their size is comparable to the desired coatings thickness, and they contribute significantly to roughness. A common way to address the macroparticle issue is to guide the plasma away from the cathode towards the substrate which is placed outside the line-of-sight to the cathode. Numerous filter concepts have been demonstrated (for a review see [6]). The most-often used approach is a bent solenoid filter, originally introduced some 30 years ago in the Soviet Union [7] and today commercially available e.g. as double-bend filter [8].] or as a light-weight, open coil structure [9]. Obviously, the latter lends itself to space applications. Figure 1 shows a 90° open-architecture filter, which is essentially an open, bent solenoid. An elegant, low-cost solution is to run arc current and filter coil current electrically in series.

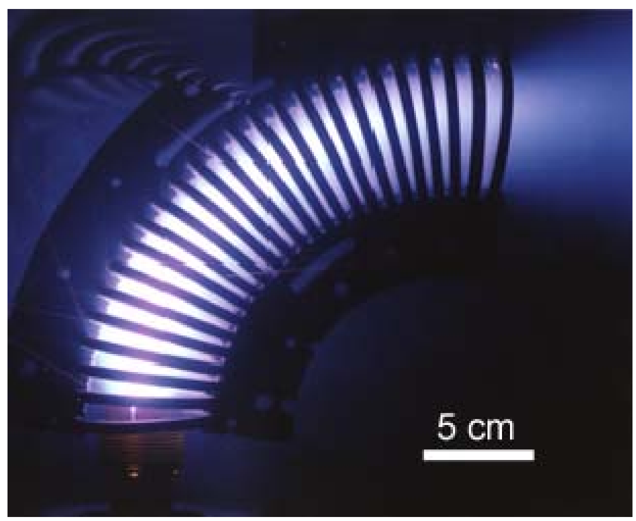

Fig. 1 90° (quarter-torus) open-architecture filter, a bent solenoid, which is used to filter macroparticles from a cathodic vacuum arc. The plasma source is at the left bottom and the filtered plasma is leaving the filter at the right top corner, streaming to the right.

MINITUARIZATION OF FCA COATING TECHNOLOGY USING PULSED ARCS

A commercially less utilized approach to coatings involves the use of *pulsed* cathodic arcs, which enables miniaturization of the arc source and its power supply. Pulsed arc sources of approximately 250 g have been developed and successfully used for small area coatings [10]. These sources exhibit excellent pulse reproducibility; however, present-generation pulsed sources have a limited figure of merit. This figure of merit can be defined as the product of coatings area and thickness, or, equivalently, the total mass deposited before a major maintenance, like a cathode replacement, is required.

To overcome the limitation associated with limited cathode life time due to cathode erosion, a cathode feed mechanisms can be employed. For example the cathode can be pushed through its holding ceramic sleeve as its surface is consumed by the plasma-producing processes. This has been demonstrated in conjunction with a repetitive self-triggering mechanisms [11].

Pulsed sources have the great advantages that they can be operated without water or other coolant. Radiative cooling is sufficient provided the *average* power is small enough.

For comparison, let's return for a moment to a conventional arc source operating in DC mode. To obtain a stable arc, the current should not be smaller than 50 A, and preferably 100 A or even greater. The arc voltage is almost independent of the arc current [12] and typically about 20 V. That is, a typical DC arc requires power of at least 1 kW. Such power is a dual problem is space, namely, it represents a large load on the supply system, and it will readily lead to overheating and destruction of the arc source components. Therefore, *pulsed* arcs offer an elegant solution because they combine the necessary power level during the on-time with a low average power based on a relatively low duty cycle. For example, using arc pulses of about 100 μs with a pulse repetition rate of 10 p.p.s. would result in a duty cycle of $\delta = 10^{-3}$. The corresponding average power is only 1 W or a little larger, depending on the peak current! Obviously, heating is not an issue but it comes at the price of a very small average deposition rate. From these estimates we can easily see that a useful space apparatus should be pulsed but its duty cycle should not be too small, i.e. clearly greater than 10^{-3}. Pulsed systems have been shown to become efficient and reliable by using much higher peak currents of the order of 1 kA. Still, using a duty cycle of 10^{-3}, an arc voltage of 20 V, a current of 1 kA at a duration of 100 μs, the average power is still a comfortably small 20 W, allowing us to use miniaturized components without forced cooling. Cooling by thermal radiation is sufficient.

INDUCTIVE ARC POWER SUPPLIES AND MINIATURE VACUUM ARC THRUSTERS

The arc deposition system is depending on a suitable power supply. Conventional pulsed sources make use of pulse-forming-networks (PFNs), which allow the operator to produce current pulses with flat, close-to-rectangular shape. Such PFN can be relatively massive when long pulses (1 ms or longer) are desired. Miniaturized supplies for pulsed arcs have been demonstrated when vacuum arc thrusters (VAT) were developed for station-keeping missions [2]. Miniaturization was pushed beyond would be needed for an efficient space coatings apparatus. The so-called vacuum arc micro thruster (VAμT) made use of inductive energy storage, as opposed to the conventional capacitive storage (Fig. 2).

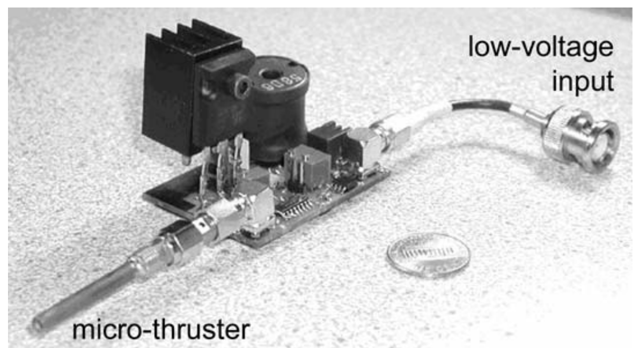

Fig.2 Photo of the miniaturized arc power supply originally developed for a vacuum arc micro-thruster. The "large" cylinder on the circuit board is for inductive energy storage.

The electrical schematic of such device is shown in Figure 3. The basic idea was to use the low voltage bus of a solar panel power system of a satellite or other space-based facility. The low voltage is typically in the range 12-24 V. A key accomplishment was to show that even when the supply voltage was less than the burning voltage of an arc (~ 20 V), the pulsed arc could be sustained for a designed pulse time due to voltage generation from the inductive storage. A solid-state switch (like an IGBT) is used to interrupt the current flow through the inductor coil *L*, which will induce a significant voltage (~ 100 V) that is high enough to start the arc via the self-triggering mechanisms [11]. The inductively stored energy is sufficient to support the arc current for a limited time.

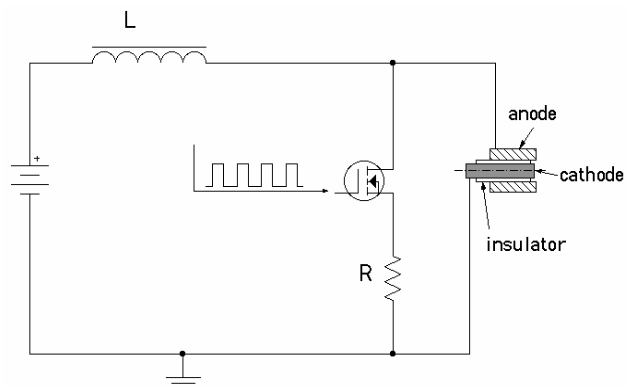

Fig. 3 Simplified schematic of the inductive energy storage and supply to the pulsed vacuum arc. The switch element is an IGBT controlled by a 5 V (TTL) signal.

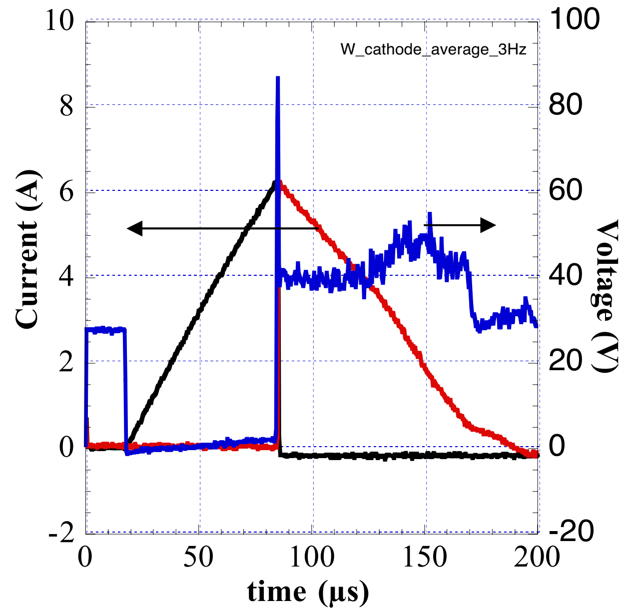

Fig. 4 Measured voltage (blue), current through the IGBT (black) and arc current (red) driven by the inductive supply shown in Fig. 2.

ESTIMATE OF PERFORMANE OF A SPACE DEPOSITION SYSTEM

In the space environment it is envisaged that the FCAD technology would be designed for minimum weight and maximum reliability.

The first generation space applications will probably involve the deposition of highly reflecting metal films, such as silver and aluminum. The design of a light weight FCAD prototype could be simple and robust using the already demonstrated pulsed vacuum arc technology with inductive energy supply. Larger area coatings can be obtained by moving the miniature coating head with robotics along the to-be-coated surface.

To illustrate the possibilities and challenges, let's consider the coating performance of the already demonstrated technology of miniature pulsed arcs and the inductive power supply with a total mass of less than 300 g.

A typical voltage-current characteristic is shown in Fig.4.

In the thruster experiment of Figure 4, a tungsten cathode was used because of the goal to produce maximum thrust. Tungsten is known to be the most challenging material in terms of arc operation (cohesive energy rule [13]) and therefore the voltage is very noisy. One should note that in this example, a burst mode was selected to optimize the use of the inductive principle while minimizing the average load to power supply and thruster.

The illustration 4 is shown because it realistically shows the pulse length (~ 100 µs or less) and current amplitude (~ 10 A or less) obtained with such miniature, light-weight supply. For the sake of an estimate, let's assume a current of $I_{arc} = 10\ \text{A}$, a duration of 100 µs, a pulse repetition rate of 5 kHz (giving a pulse duty cycle of $\delta_{pulse} = 50\%$) and a burst duty cycle of $\delta_{burst} = 50\%$. Let us further assume a typical ion erosion rate of $\gamma_i = 20\ \mu\text{g/C}$ and a filter efficiency of $\varepsilon_{filter} = 0.25$ (ratio of ions leaving the filter vs. entering it). With these numbers we can calculate the metal mass rate that is provided from the miniature filtered arc source in the form of ions via the expression

$$\frac{M_{depos}}{t_{depos}} = I_{arc} \gamma_i \delta_{pulse} \delta_{burst} \varepsilon_{filter} \qquad (1)$$

resulting in a rate of 12.5 µg/s. Now, we can translate this in the time required to coat certain area. For example, let's consider an area of A= 1 m^2 to be coated with 50 nm of silver (thickness *s*) to make a reflector. The mass of that coating is

$$M_{depos} = \rho A s \qquad (2)$$

where ρ is the mass density, which, for filtered arc coatings, is very close to the bulk density (silver 10.5 g/cm^3). In the example, M_{depos}=0.525 g. Combining equations (1) and (2) gives us 42,000 s or 700 min or close to 12 hours of deposition time.

This estimates shows, on the one hand, that existing miniature and light-weight FCVA technology could be used to make coatings of relevance, for example producing a coating on a telescope mirror, on the other and there are significant challenges to the technology development when considering coatings of truly large area, as considered for solar sails. Obviously, the requirements of 300 g mass and other restrictions on the deposition system will have to be relaxed to make true large area coatings viable. In the foreseeable future, the FCVA appears to be viable for high-value deposition in space, such as metallizing the imaging mirror surface of a telescope, whereas vary large area coatings have to be done on earth or by a much further developed, more economical technology.

The main advantage of a space-based coatings approach is likely to be found were the highest quality of a metal coating is required. The combination of the energetic, self-ion-assisted condensation process using filtered cathodic arc plasma and the superior vacuum of the lunar space promises extremely smooth, dense, and thus superior metals films, which are of great value to post-Hubble telescopes. Furthermore, space-based coating is unique in enabling repair of coatings in space, which may be necessary after a mirror surface is damaged by the impact of micrometeorites or similar events.

Finally, we may expand on the theme by assuming that space-based coatings have be realized and scaled, either by relaxing the 300 g mass limitation or by having developed novel designs that overcome the limits of today's terrestrially tested miniature arc sources. Under this assumption, large area coatings are feasible, opening a range of other possible applications [3]. Among them are

- Space Antennas
- Solar Arrays
- Solar Sails
- Reflectors for thermal control
- Reflectors for power generation,

to name a few.

CONCLUSIONS

In this contribution it was argued that there is a need for coatings in space because this technology can greatly benefit the ambitious goals of the further exploration of Moon and Mars as well as the production of mirrors of a moon-based large telescope. Technologically, there are several factors that make this approach promising and feasible, namely,

- The demonstrated superior quality of films made by filtered cathodic arc deposition (FCAD);
- The recent development of miniature, light-weight, filtered cathodic arc sources;
- The recent development of miniature, light-weight arc power supplies for so-called micro-vacuum-arc thrusters, using low bus voltage and inductive energy storage;
- The extreme vacuum of space such as on the lunar surface is well suited to produce silver and aluminum mirrors with much lower contamination levels than can be done on earth.

Using the currently defined weight limit of 300 g for both the filtered arc source and power supply, it was estimated that a mirror of 1 m^2 can be coated with silver in a time frame of about 12 hours. Large area coatings, involving thousands or more square meters, may be possible if the 300 g limitation is relaxed or new solutions are identified. The greatest value of space-based coatings is in the superior metallization quality than be expected, leading a higher index of reflection, and the ability to perform on-site repair, if necessary.

The deployment of large-area space-based coatings manufacturing will be depend on the economics of the process versus manufacturing on Earth and transport to space. It is already clear that space-based coatings for high-value applications on relatively small areas, such as the production of an imaging mirror surface of unsurpassed quality, can be done and should be done in space.

During the "International Conference Moon Base: a Challenge for Humanity Venice Workshop, May 26-27, 2005 IAES - Washington Workshop, October 11-12, 2005, WAS" many of the technological issues confronting lunar colonization were presented [14]. The impetus for returning to the moon is growing both in the US and Europe.

This contribution to the spectrum of potential lunar technologies is designed to enable the production of large-area telescope mirrors and space solar power reflectors. In addition, the proposed lunar living structures can be coated, using robotically controlled FCA deposition, with IR and UV protective films that will provided a cost effective method for establishing human habitats for future generations of space travelers.

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REFERENCES

[1] C. W. Sir Shults III, "Private Communication," 2005.

[2] J. Schein, N. Qi, R. Binder, M. Krishnan, J. K. Ziemer, J. E. Polk, and A. Anders, "Low mass vacuum arc thruster system for station keeping missions," presented at 27th International Electric Propulsion Conference, Pasadena, CA, 2001.

[3] M. L. Fulton, "Future space-based deposition technology for solar power and astronomical applications," presented at 48th Annual Technical Conference Proceedings, Society of Vacuum Coaters, Denver, CO, 2005.

[4] A. Anders, "Ion charge state distributions of vacuum arc plasmas: The origin of species," *Phys. Rev. E*, vol. 55, pp. 969-981, 1997.

[5] A. Anders and G. Y. Yushkov, "Ion flux from vacuum arc cathode spots in the absence and presence of magnetic fields," *J. Appl. Phys.*, vol. 91, pp. 4824-4832, 2002.

[6] A. Anders, "Approaches to rid cathodic arc plasma of macro- and nanoparticles: a review," *Surf. Coat. Technol.*, vol. 120-121, pp. 319-330, 1999.

[7] I. I. Aksenov, V. A. Belous, V. G. Padalka, and V. M. Khoroshikh, "Apparatus to rid the plasma of a vacuum arc of macroparticles," *Instrum. Exp. Tech.*, vol. 21, pp. 1416-1418, 1978.

[8] X. Shi, B. K. Tay, D. I. Flynn, Q. Ye, and Z. Sun, "Characterization of filtered cathodic vacuum arc system," *Surf. Coat. Technol.*, vol. 94-5, pp. 195-200, 1997.

[9] A. Anders and R. A. MacGill, "Twist filter for the removal of macroparticles from cathodic arc plasmas," *Surf. Coat. Technol.*, vol. 133-134, pp. 96-100, 2000.

[10] R. A. MacGill, M. R. Dickinson, A. Anders, O. R. Monteiro, and I. G. Brown, "Streaming metal plasma generation by vacuum arc plasma guns," *Rev. Sci. Instrum.*, vol. 69, pp. 801-803, 1998.

[11] A. Anders, I. G. Brown, R. A. MacGill, and M. R. Dickinson, ""Triggerless" triggering of vacuum arcs," *J. Phys. D: Appl. Phys.*, vol. 31, pp. 584-587, 1998.

[12] R. L. Boxman, D. M. Sanders, and P. J. Martin, *Handbook of Vacuum Arc Science and Technology*. Park Ridge, N.J.: Noyes Publications, 1995.

[13] A. Anders, "Cohesive energy rule for vacuum arcs," in *Emerging Applications of Vacuum-Arc-Produced Plasma, Ion and Electron Beams, NATO Science Series II. Mathematics, Physics and Chemistry vol. 88*, I. Brown and E. Oks, Eds. Dordrecht: Kluwer Academic Publishers, 2002, pp. 1-14.

[14] Proceedings found on the website: http://www.moonbase-italia.org/homepage.htm