Combustion technologies need to be monitored and controlled in order to meet increasingly stringent environmental regulations. In particular, diesel exhaust contains both gas and particle phases that pose risks to the environment and to human health and safety.\textsuperscript{1-3} This particulate matter (PM) or soot is a complex mixture containing many individual components that can be classified by size and composition. In terms of health effects, the most hazardous sizes likely include fine (2.5 μm diameter or less, so-called PM\textsubscript{2.5}) and ultrafine (less than 100 nm diameter), which are also the most difficult to measure with available technologies.\textsuperscript{4,5} These PM\textsubscript{2.5} levels are of increasing concern since many strategies for diesel exhaust after-treatment systems to improve fuel efficiency and decrease the amount of harmful gases also tend to increase the amount of dangerous fine or ultrafine PM.\textsuperscript{3} Therefore, improvements in PM sensing technologies that directly measure exhaust and could meet the more stringent on-board diagnostic (OBD) requirements for self-diagnosis and reporting in automotive applications are needed to evaluate and control diesel exhaust after-treatment systems in real time.

PM detection methods for vehicle certification have traditionally required gravimetric filter methods that involve drawing specified volumes of diluted exhaust; however, in-situ methods with higher sensitivity are needed to address decreasing PM levels in newer technologies.\textsuperscript{4} In-situ sensor technologies are typically based on either resistive techniques that detect soot accumulation\textsuperscript{5-7} or electrostatic methods that determine real-time particle concentrations.\textsuperscript{10,11} A recently developed, low-cost electrostatic in-situ PM measurement approach has demonstrated both higher sensitivity and better durability compared to resistive techniques.\textsuperscript{8-11} This novel electrostatic PM sensor is based on a concentric electrode design with a central cylindrical high-voltage electrode at approximately +1 kV surrounded by an inner baffle that serves as the ground/negative terminal; a venturi produces the observed current amplification.\textsuperscript{12} New sensor electrodes typically require a few minutes of operation, or so-called “startup time”, in the exhaust PM before reaching the expected amplified signal magnitude. Exposure to higher PM concentrations tended to decrease the measured startup time. Furthermore, previously operated sensors demonstrated better performance in terms of a reduced startup time to reach the amplified signal magnitude.

Bilby et al.\textsuperscript{12} investigated the amplification effect using an electrostatic trap and attributed the origin of the signal to the collection of naturally present electrically charged particles onto the electrodes; however, they found that the measured current was approximately 100 times larger than carried by the soot. Furthermore, they found that the amplification was not immediate, but followed a quiescent period that was inversely proportional to soot concentration, and that large highly charged particles appeared at the trap exit, of order 10 µm and carrying tens to hundreds of charges. Bilby et al. also found that dendritic soot structures grew aligned with the electric field and collapsed when the electric field was removed; they then formulated a kinetic model based on the dendrites growth to a critical height at which the electric field force exceeds the binding force, and then the highly charged dendrites fragment and deposit on the opposite electrode propagating a chain reaction of dendrite growth, fragmentation, and charge transport that produces the observed current amplification.\textsuperscript{12}

Electrodeposition of three-dimensional dendritic features onto the surfaces of the central high-voltage cylindrical electrode was investigated as a means of altering the growth of soot onto electrodes and potentially reducing the quiescent startup time of new PM

The sensing principle of the novel electrostatic PM approach is not completely understood; however, the response seems to rely on the capture of the naturally combustion charged particles on electrode surfaces.\textsuperscript{8} Captured particles assemble or agglomerate via electrostatic force-directed assembly into filamentous structures with high surface charge density at filament tips, resulting in up to three orders of magnitude increase in measured charge current amplification.\textsuperscript{8} New sensor electrodes typically require a few minutes of operation, or so-called “startup time”, in the exhaust PM before reaching the expected amplified signal magnitude. Exposure to higher PM concentrations tended to decrease the measured startup time. Furthermore, previously operated sensors demonstrated better performance in terms of a reduced startup time to reach the amplified signal magnitude.

Figure 1. Schematic of PM sensor cross-section.
sensors. Three-dimensional surface structures have been shown to act as conductive networks, yielding electrodes with high energy and power density in supercapacitor applications. Alloys of nickel and cobalt oxides produced by thermal decomposition, chemical bath deposition, hydroxide decomposition, the sol-gel method, and electrodeposition have been explored for their use in electrical applications due to the high specific capacitance, low resistance, and excellent charge-discharge cycle stability offered by the binary transition metal oxide system.

The structure and properties of an electrically deposited surface are highly dependent on the parameters of the electrodeposition process. Parameters that must be taken into consideration and optimized during electrodeposition using a conventional three-electrode cell include chemical composition, pH and temperature of the electrolytic bath, shape, position, surface preparation, and movement of the working electrode in the bath, and applied current density limits, number of current cycles employed during deposition, and time allowed for each current cycle. Each of the aforementioned parameters is influential in forming the microstructure of electrically deposited films. The present work investigates the role of several of these parameters in the growth of three-dimensional dendritic Ni-Co coatings on 304 stainless steel based on an electrodeposition method proposed by Silva, et. al. The applied lower current density limit and number of applied current cycles were varied in subsequent experiments, and their influence on attributes such as height, spacing, and orientation of the deposited surface features was noted. Furthermore, the dendritic Ni-Co coatings were used on the high-voltage electrodes of electrostatic PM sensors to determine the effect of these microstructures on the startup times of the sensors in diesel PM exhaust.

Experimental

Electrodeposition of dendritic Ni-Co coatings onto PM sensor test electrodes were carried out in a 600 mL beaker containing an aqueous solution of 0.04 M CoCl2·6H2O, 0.06 M NiCl2·6H2O, and 0.5 MH3BO3 (Aldrich). A 2 M solution of NaOH was prepared and added dropwise to bring the electrolytic solution to a pH of 5.5. A standard three-electrode electrochemical cell was employed for the electrodepositions, with a saturated calomel electrode as a reference electrode and a platinum wire as a counter electrode. The PM sensor test electrodes were machined from AISI 304 stainless steel in the form of cylinders approximately 8.5 mm in diameter and 23.5 mm in length and used as the working electrode during electrodeposition. The surface of the PM sensor working electrode cylinders was bead blasted (Blast-It-All LB 4024-3), rinsed with DI water, and dried in air, providing a clean and uniformly rough surface for enhanced dendritic adhesion. The working electrode cylinders were attached to an electrode rotator (Compact Pine Rotator) set to 30 rotations per minute. A galvanic square wave cathodic current was applied to the electrode cylinders at room temperature during deposition using a potentiostat/galvanostat (Solartron 1287 Electrochemical Interface) and CorrWare software (Scribner Associates). Two different sets of experiments were used to investigate the influence of the sensor’s surface microstructure on sensor performance, first by altering the lower current density limit and then by altering the number of applied current cycles. All experiments employed an upper current density limit of −20 mA cm−2. In the first set of experiments, electrodeposition of Ni-Co onto the working electrode cylinders employed three different deposition conditions with lower current density limits of −15, −20, or −25 mA cm−2. Current was applied for 20 cycles for a period of 50 seconds for each electrode cylinder. In the second set of experiments, the applied cycles were varied from 6 to 35 cycles for a period of 50 seconds while the lower and upper current density limits were held constant at −20 and −3 mA cm−2, respectively.

Microstructures of the electrodeposited coatings were analyzed at the top, middle, and bottom of the cylinders by scanning electron microscopy (SEM, Hitachi SU8030), and microstructures at the middle of the cylinders were analyzed by laser scanning digital profilometry (Olympus LEXT OLS4100). Surface height plots were generated from the profilometry data using ImageJ2 software, while statistical analyses and probability distributions were generated using MATLAB. The startup time of Ni-Co coated electrode cylinders was evaluated using a concentric electrostatic PM sensor test housing that allowed for the electrical connections and venturi to draw exhaust gas through the sensor components as well as for placement into the exhaust gas manifold. The Ni-Co coated electrode cylinder served as the central high-voltage electrode and the surrounding inner baffle as the ground/negative terminal.

An electronics module developed by CoorsTek Sensors was employed for sensor operation. The module contains a voltage source of 1 kV DC with galvanic isolation. The negative side of the source is attached via a high impedance current measurement circuit to chassis/system ground and the positive side of the source is attached directly to the electrode cylinder. The current measurement circuit was then used for detecting the sensor current response to exhaust PM in 0.1 nA steps. The module was developed for ease of deployment for vehicle testing but the same measurement can be made using a laboratory grade isolated high voltage supply and a current measurement instrument of sufficient resolution.

A 4 kW diesel generator (Onan Genset 4.0) with Simplex Swift-EFT load bank generated exhaust PM, where the PM concentration was controlled and stabilized by diluting the exhaust with air from a blower by more than ~80%. The blower was used to achieve a target PM concentration of ~3.5 mg m−3 and resulted in an engine gas temperature of ~80 °C. Figure 2 shows a simplified schematic of the engine test setup. The PM content was monitored using a light scattering photometer (DustTrak Aerosol Monitor) to provide a reference measurement. In each test, four Ni-Co coated electrode cylinders were measured alongside two controls (i.e., uncoated and unpolished electrode cylinders) and two sensors previously operated in exhaust PM, or so-called “pre-operated” sensors. The startup times of each respective set of samples, controls, and pre-operated sensors were averaged for comparison.

Results and Discussion

Varying lower current density limits.—Morphology.—The microstructure resulting from electrodeposition of Ni-Co at a lower current density limit of −15 mA cm−2 and 20 cycles is presented in Fig. 3. Images were taken at three different locations along the electrode cylinder length. Figure 3a depicts a cylinder location most deeply submerged in the plating bath, herein referred to as the bottom of the cylinder, while Fig. 3b was taken at the middle of the cylinder. Figures 3c and 3d were taken at a cylinder location close to the top of the plating solution in the beaker. Morphology differences occurred along the length of the cylinders, which could have resulted from the closer proximity of the platinum wire counter electrode tip to the bottom of the electrolytic bath producing a stronger localized electric field. There were no fully grown dendritic structures on the surface of the cylinder after deposition at a lower current density limit of −15 mA cm−2.

Figure 4 depicts the microstructure resulting from electrodeposition of Ni-Co at a lower current density limit of −20 mA cm−2 and 20 cycles. Figures 4a and 4b represent the bottom and middle, respectively, of the electrode cylinder after deposition, while Figs. 4c and 4d both represent the top of the coated cylinder. Deposition at a lower current density limit of −20 mA cm−2 followed
similar trends, in terms of height and spacing of structures, along the length of the cylinder as the deposition at a current density limit of $-15$ mA cm$^{-2}$ discussed previously. Dendrites appeared to grow most readily at the bottom of the cylinder, in the portion most deeply submerged in the plating bath, with growth diminishing along the length of the cylinder toward the top of the plating bath. Overall, it was clear that a lower current density limit of $-20$ mA cm$^{-2}$ was more preferable for dendritic growth than was a lower current density limit of $-15$ mA cm$^{-2}$.

Figure 5 shows the microstructure of the electrodeposited Ni-Co at a lower current density limit of $-25$ mA cm$^{-2}$ for 20 cycles. Figure 5a was taken at the bottom of the electrode cylinder, while Figs. 5b, 5c and 5d were taken closer to the top of the cylinder. The structures at a lower current density limit of $-25$ mA cm$^{-2}$ were much larger and more homogeneous than those resulting from the previous two conditions that used current density limits of $-20$ and $-15$ mA cm$^{-2}$. Furthermore, Ni-Co dendrites appeared more fully grown and more closely spaced together than those of the two previously discussed deposition conditions.

Surface height plots taken from the middle of the cylinders for Ni-Co deposited at lower current density limits of $-15$, $-20$, and $-25$ mA cm$^{-2}$ are shown in Figs. 6a, 6b, and 6c, respectively, and Fig. 7 displays the amplitude probability distribution functions. The amplitude probability distribution function describes the probability of surface feature heights with a given value. In Fig. 7, the y-axis is depth or the distance relative to the height of the tallest feature on the surface and decreases from top to bottom. For example, a depth of 0 $\mu$m is equivalent to the height of the tallest feature, and the maximum depth would indicate the base of the feature. Statistical analyses of the profilometry data are summarized in the inset table of Fig. 7.

In Fig. 7, the amplitude probability distribution function for the $-15$ mA cm$^{-2}$ deposition condition has a relatively narrow distribution symmetric about a depth of 20 $\mu$m indicating minimal variation in peak size and a long tail distribution that extends from 35 $\mu$m to 58 $\mu$m with very low probability and minimal occurrence. The data can be used to approximate a median surface feature height of 38 $\mu$m, where 0 $\mu$m depth corresponds to a height of 58 $\mu$m and the median can be calculated by then subtracting the depth indicated by the peak of the narrow distribution (20 $\mu$m). The amplitude probability distribution function for the $-20$ mA cm$^{-2}$ deposition condition showed that both surface roughness and peak size variation increased when compared to the $-15$ mA cm$^{-2}$ deposition condition. The peak of the distribution function moved toward smaller values of depths, suggesting that the tallest features on the surface were sharp with a fair amount of spacing between them. Furthermore the upper tail of the distribution function is weighted more toward the minimum depth, which suggests that the mean height of the surface features was larger than the median height, roughly 48 $\mu$m, as the median of the distribution function occurs at a depth of 85-100 $\mu$m. Finally, the amplitude probability distribution function for the $-25$ mA cm$^{-2}$ deposition condition is nearly symmetric about a depth of approximately 42 $\mu$m with a long tail extending from 65 $\mu$m to 110 $\mu$m with very low probability and minimal occurrence. As a depth of 115 $\mu$m corresponds to the base of the substrate, the distribution function indicates a high concentration of features at a height around 73 $\mu$m. The probability distribution functions suggest that dendritic growth is encouraged by changing the magnitude of the lower current density limit from $-15$ to $-25$ mA cm$^{-2}$.
Figure 6. Surface height plots taken from the middle of the cylinders for the Ni-Co coating deposited using 20 cycles at lower current density limits of (a) $-15 \text{ mA cm}^{-2}$, (b) $-20 \text{ mA cm}^{-2}$, and (c) $-25 \text{ mA cm}^{-2}$. All scale bars are $200 \mu\text{m}$.

PM sensor performance.—The electrode cylinders coated with Ni-Co using the three different deposition conditions were then tested in exhaust using a PM sensor test housing. Figure 8 depicts the average results from the startup testing of multiple cylinders. Ni-Co coated electrode cylinders were tested alongside control test sensors that used uncoated and unpolished cylinders and test sensors with pre-operated electrode cylinders. In each plot of Fig. 8, the time elapsed from the introduction of exhaust PM to the test sensors is plotted versus the “normalized gain” of the measured test sensor signal output. The gain of the test sensor is defined as the measured current output, in nA, divided by the measured PM concentration, in mg m$^{-3}$. A “full gain” value is found by averaging the gain values for the last 100 seconds of exposure to PM during testing at the constant soot concentration. The normalized gain is then the gain divided by the full gain (and therefore unitless) and provides a more suitable metric for comparing startup times compared to the raw measured current output of the sensor, which may become distorted due to fluctuations or other anomalies in the PM concentration.

The test sensors with cylinders coated at the $-15 \text{ mA cm}^{-2}$ lower current density limit, presented in Fig. 8a, exhibited a slower response in startup time than did the control test sensors, while the test sensors with cylinders coated at a lower current density limit of $-20 \text{ mA cm}^{-2}$, presented in Fig. 8b, exhibited a slightly faster response than the controls. The test sensors with cylinders coated at $-25 \text{ mA cm}^{-2}$, presented in Figure 8c, showed slightly faster startup times initially, but proved to have a slower response than the controls at later times.

The full gain value discussed above was also used to calculate the elapsed time to reach either 10% or 63% of the full gain value, respectively denoted t10 and t63. The difference in t10 and t63 between the controls and the coated cylinders are presented in Fig. 9.
Figure 8. PM sensor testing evaluation of startup time comparing the behavior of uncoated control cylinder electrodes, pre-operated cylinder electrodes, and electrode cylinders coated with Ni-Co deposited using 20 cycles and lower current density limits of (a) $-15 \text{ mA cm}^{-2}$, (b) $-20 \text{ mA cm}^{-2}$, and (c) $-25 \text{ mA cm}^{-2}$.

While a positive change in time between the control response and the response of the coated cylinder represents a faster response for the coated cylinder, a negative time change represents a lag between the response of the control and the response of the coated cylinder. The time change values reported in Fig. 9 reflect the plots in Fig. 8. The cylinders coated at a lower current density level of $-15 \text{ mA cm}^{-2}$ showed an overall slower response than the controls, having negative values for $\Delta t_{10}$ and $\Delta t_{63}$ of $-44$ and $-64$ sec, respectively, while the sample coated at a lower current density level of $-20 \text{ mA cm}^{-2}$ showed a consistently faster response than the control, yielding positive values for $\Delta t_{10}$ and $\Delta t_{63}$ of 27 and 67 sec, respectively. Furthermore the sample coated at a lower current density level of $-25 \text{ mA cm}^{-2}$ showed an initially faster response with a lag at later times, reflected in the positive value for $\Delta t_{10}$ of 7 sec and the negative value for $\Delta t_{63}$ of $-108$ sec.

Varying cycle number.—Morphology.—Since the $-20 \text{ mA cm}^{-2}$ deposition condition seemed to have better performance in startup sensor testing compared with either the $-15$ or $-25 \text{ mA cm}^{-2}$ deposition conditions, the influence of varying the cycle numbers was investigated while keeping the lower current density limit constant at $-20 \text{ mA cm}^{-2}$. Cycle numbers were varied from 6 to 35 cycles. Figure 10 shows the microstructure resulting from electrodeposition of Ni-Co on electrode cylinders using the smallest number of cycles investigated, the 6 cycle deposition condition. Figures 10a and 10b were taken at the bottom of the cylinder, while Fig. 10c was taken at the top of the cylinder. Similar to the previously discussed deposition conditions that varied the lower current density limit, surface features resulting from the 6 cycle deposition condition were inhomogeneous along the length of the cylinder. Fully grown dendritic structures were found near the bottom of the cylinder, with growth extending, although appearing increasingly sparser, approximately $500 \mu m$ from the bottom edge of the sample. The microstructure resulting from the 15 cycle deposition condition is presented in Fig. 11. Figures 11a, 11b, and 11c were taken at the bottom, middle, and top of the cylinder, respectively. While dendritic growth along the length of the cylinder remained inhomogeneous for the 15 cycle deposition condition, the images showed a trend toward the increasing growth of Ni-Co structures with increasing cycle numbers.

The microstructure resulting from the 25 cycle deposition condition is presented in Fig. 12. Figures 12a, 12b, and 12c were taken at the bottom, middle, and top of the cylinder, respectively. The dendritic growth along the length of the cylinder became more homogeneous for the 25 cycle deposition condition, with the images showing a trend toward the increasing growth of Ni-Co structures with increasing cycle numbers.
Figure 11. SEM images of the Ni-Co surface coating deposited using a lower current density limit of $-20 \text{ mA cm}^{-2}$ and 15 cycles at different locations along the cylinder: (a) bottom (scale bar of 10 $\mu$m) (b) middle (scale bar of 10 $\mu$m), and (c) top (scale bar of 10 $\mu$m).

Ni-Co deposited after 25 current cycles was far more homogeneous than those deposited at the lower numbers of current cycles. Fully grown and densely packed dendrites were seen in the middle of the cylinder, while smaller structures were present at the top of the cylinder and a low number of fully grown structures dispersed throughout. Growth at the top of the cylinder for the 25 cycle deposition condition was more complete compared with previously discussed cylinders deposited using lower cycle numbers.

Figure 13 depicts the microstructure resulting from the 35 cycle deposition condition. Figure 13a was taken at the bottom of the cylinder, while Figs. 13b and 13c were taken at the middle and top of the cylinder, respectively. While fairly uniform growth was seen throughout the length of this cylinder, anomalously large structures arose on the surface after the 35 cycle deposition condition.

Surface height plots taken from the middle of the cylinders for Ni-Co deposited using 15 and 25 current cycles are presented in Figs. 14a and 14b, respectively, and Fig. 15 displays amplitude

Figure 12. SEM images of the Ni-Co surface coating deposited using a lower current density limit of $-20 \text{ mA cm}^{-2}$ and 25 cycles at different locations along the cylinder: (a) bottom (scale bar of 50 $\mu$m) (b) middle (scale bar of 50 $\mu$m), and (c) top (scale bar of 500 $\mu$m).

Figure 13. SEM images of the Ni-Co surface coating deposited using a lower current density limit of $-20 \text{ mA cm}^{-2}$ and 35 cycles at different locations along the cylinder: (a) bottom (scale bar of 500 $\mu$m) (b) middle (scale bar of 500 $\mu$m), and (c) top (scale bar of 500 $\mu$m).

Figure 14. Surface height plots taken from the middle of the cylinders for the Ni-Co coating deposited at lower current density limits of $-20 \text{ mA cm}^{-2}$ and (a) 15 cycles and (b) 25 cycles. All scale bars are 200 $\mu$m.
In Fig. 15, the distribution for the 15 cycle deposition condition is mostly symmetric about a depth of 21 μm. The narrow elongated appearance of the distribution indicates that peak size variation was minimal. Figure 15 also shows that for the 15 cycle deposition condition, a depth of roughly 38 μm correlates to the base of the surface structures, and that the median surface feature height was approximately 17 μm. The distribution for the 25 cycle deposition condition is centered about a depth of approximately 60 μm; however, the curve is skewed toward lower depths. Similar to the distribution function for the Ni-Co deposition at a lower current limit of −20 mA cm⁻² and 20 current cycles (see Fig. 7), the 25 cycle deposition behavior suggests that the tallest features were sparse on the surface. The effect can also be seen in the corresponding surface plot (Fig. 14b). The upper tail of the distribution for the 25 cycle deposition condition in Fig. 15 extends to lower depths and suggests that the mean height was larger than the median height. These probability distributions indicate that the growth of surface features intensified as the number of applied current cycles was raised.

**PM sensor performance.**—Electrode cylinders were then tested in exhaust using PM sensor test housings alongside control uncoated test sensors and test sensors with pre-operated electrode cylinders, as previously discussed. The startup PM sensor behavior for the 15 and 25 cycle deposition conditions is shown in Fig. 16. The 15 cycle deposition condition exhibited an overall faster startup response than the controls. The 25 cycle condition, however, showed a slightly faster response at the beginning of startup testing, but as testing continued the response lagged behind that of the controls.

As described above, a full gain value was then found for samples and controls, and t₁₀ and t₆₃ were accordingly determined. The differences in t₁₀ and t₆₃ between the controls and the coated samples are presented in Fig. 17. The differences in response times for the sample coated at a lower current density limit of −20 mA cm⁻² for 20 current cycles is given for reference. The positive changes in time values between the samples coated at the 15 cycle deposition condition and the uncoated controls reflect the faster startup time performance seen in Fig. 16a. Furthermore, the 15 cycle deposition condition showed faster response times than the 20 cycle deposition condition for reaching 10% of its full gain value (about twice as fast) and similar response times for reaching 63% of its full gain value. The 25 cycle deposition condition, however, showed no improvement in startup performance compared to the uncoated controls, failing to reach even 10% of its full gain value before being outperformed by the controls.

While the amplitude probability distribution for the deposition performed at −15 mA cm⁻² for 20 cycles, shown in Fig. 7, is almost identical to that of the deposition performed at −20 mA cm⁻² for 15 cycles, shown in Fig. 15, the dendritic coatings had nearly opposite effects on the startup times of the sensors with respect to the controls. The coating deposited at −15 mA cm⁻² for 20 cycles caused approximately a 40 sec lag in reaching 10% of its full gain value as compared to its control, while the coating deposited at −20 mA cm⁻² caused the sensor to reach 10% of its full gain value approximately 50 sec faster than its control, evidenced in Figs. 9 and 17, respectively. The height distribution of dendritic features on a sensors surface, therefore, seems...
to have no direct correlation to its startup time, and the response of a PM sensor with a dendritic Ni-Co coating is likely a consequence of multiple physical parameters.

Conclusions

Electrodeposition of three-dimensional dendritic Ni-Co coatings onto the central high-voltage cylindrical electrode in PM sensors was evaluated for improving sensor performance by decreasing the initial startup time. The influence of electrodeposition parameters on the microstructure of the dendritic Ni-Co coating was investigated by first altering the lower current density limit and then by altering the number of cycles. Both the lower current density limit and the number of current cycles controlled the overall growth of surface features, where an increase in magnitude for either parameter also increased the growth of surface features. In terms of improving the PM sensor performance by reducing startup time, the dendritic Ni-Co coating electrodeposited using a lower current density limit of \(-20 \text{ mA cm}^{-2}\) was found to have better performance than either the \(-15\) or \(-25 \text{ mA cm}^{-2}\) lower current density limits. Furthermore, for the lower current density limit of \(-20 \text{ mA cm}^{-2}\), dendritic Ni-Co coatings electrodeposited using 15 cycles seemed to have better performance than either lower or higher numbers of cycles. There seems to be an intermediate optimized dendritic Ni-Co surface coating microstructure for reducing startup time that could be related to the interaction between PM and short surface features that are higher aspect ratio and closely packed.

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