Scale-Up of Manufacturing Processes for a Bipolar Nickel-Metal Hydride Aircraft Battery

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Abstract

Electro Energy, Inc. (EEI) has developed a bipolar nickel-metal hydride (Ni-MH) wafer cell design that has the advantages of reduced size, weight, and cost, with increased high power capabilities, over conventional Ni-MH and competing technologies. These advantages make the EEI bipolar Ni-MH the battery of choice to replace main aircraft batteries. To meet the demands of the DOD, and commercial interests, while providing a cost competitive battery, it is necessary to scale-up EEI's manufacturing processes. Supported by the U.S. Air Force Manufacturing Technology Program, EEI has begun this scale-up process, focusing on three critical process steps. These include: 1) EEI's $Ni(OH)_2$ electroless nickel coating process; 2) EEI's plastic bonded positive and negative electrode rolling process; and 3) EEI's cell sealing process. This paper describes the scale-up of these key manufacturing process steps, with particular focus on reducing the cost of EEI's bipolar Ni-MH aircraft battery.

Introduction

EEI has developed a bipolar Ni-MH battery that offers increased power and three times the energy with the same weight and volume of existing fighter aircraft batteries. These advantages and the environmental friendliness of the chemistry make the battery a reasonable choice to replace existing Pb-Acid and NiCd aircraft batteries. For EEI to meet the production needs of approximately 2,000 batteries annually, it is necessary to scale-up and improve the existing R&D processes to reliable and feasible manufacturing processes. To begin this growth, EEI has been involved in multiple Manufacturing Technology Programs, supported by the U.S. Air Force.

EEI's bipolar cell design consists of one positive electrode, separator material, and one negative electrode, encased by foil current collectors laminated to plastic film sealed into a cell package. EEI's manufacturing process is shown in Figure 1.

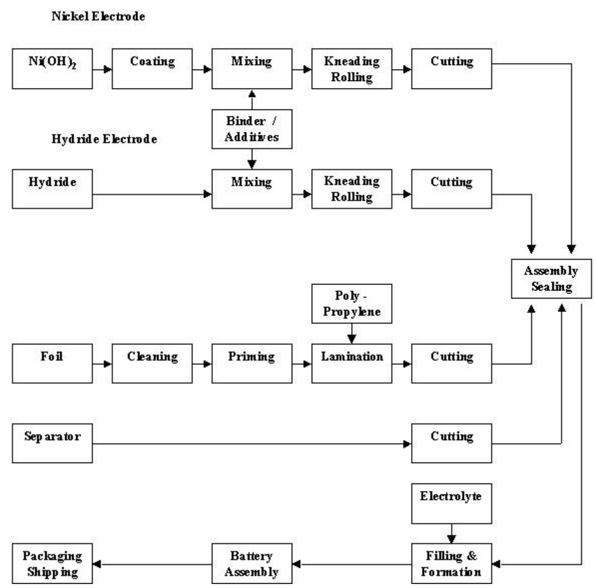

Figure1: EEI's Manufacturing Process

Three process steps were identified as the most critical in developing a manufacturing capability and reducing the overall battery cost. These steps included the $Ni(OH)_2$ electroless nickel plating, the rolling of plastic bonded positive and negative electrodes, and the cell sealing and lamination process. Significant effort has been in place to develop these into manufacturing processes and reduce the costs.

$Ni(OH)_2$ Electroless Ni Coating Process

EEI does an in-house electroless plating on commercial $Ni(OH)_2$, coating each particle with a micro-porous Ni and Co layer. Figure 2 shows a section of $Ni(OH)_2$, with a Ni/Co layer. $Ni(OH)_2$ alone is a poor electronic conductor. This process allows for an increased electrical conductivity and an overall improvement in electrochemical performance and cycle stability. This process gives EEI a distinct weight and cost advantage over other battery producers that must add 30% or more of a conductive material or expensive substrates such as nickel foam to get electrical conductivity from $Ni(OH)_2$.

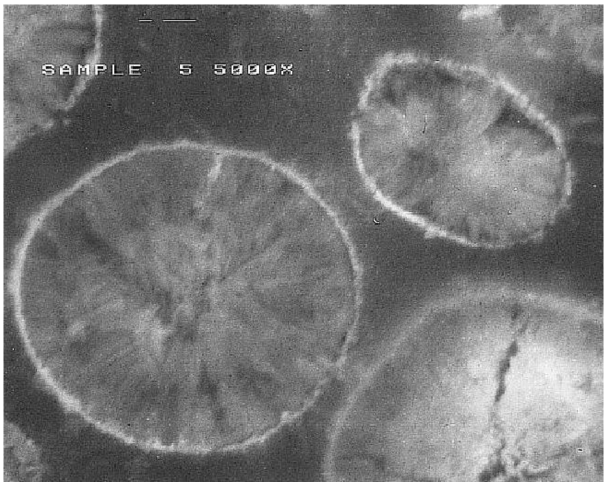

Figure 2: Section of Spherical Coated $Ni(OH)_2$

For EEI to go into production the process must first be converted from the bench top of 2 kg batches to large-scale levels using manufacturing equipment. Initial work was concentrated on directly scaling up to the 10 kg batch level, with semi-automatic control, to verify that the process could be controlled at larger levels, while producing the same quality of product. This scale-up entailed process tanks and mixers, and a filter press to filter and rinse the material. Drying was done with trays in a vacuum or convection oven. Cells using the material were built to verify the process. The scale-up was designed with the intentions that it could later be further scaled up using the same process design.

In addition, it was vital to the scale-up that process and formula improvements be made to decrease labor and material costs. The original process had three separate batch steps, which resulted in a total batch time of 6 hours, not including drying. Also, $PdCl_2$ is a critical component for the activation of the reaction, which adds up to 25% to the cost of the material. Experiments were done on a small 200g level to improve and/or reduce the process, and to eliminate or substitute expensive raw materials. Cells were made using material from each experimental batch, to verify the performance.

Electrode Rolling Processes

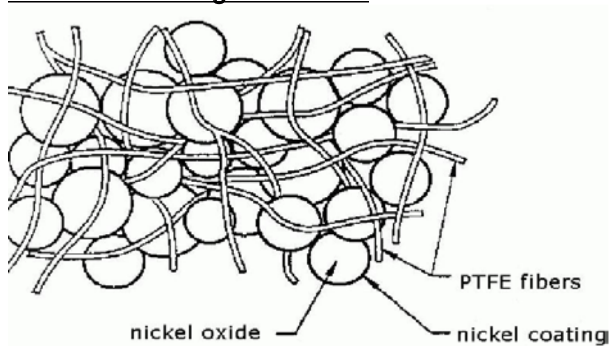

Figure 3: $Ni(OH)_2$ – Teflon Binder Matrix

EEI uses a completely dry process in making its positive and negative electrodes. Active material and any additives are dry mixed with 1% by weight Teflon. This mixed material is then kneaded and rolled into sheets, which are then cut to the actual electrode size. Figure 3 shows a schematic of the $Ni(OH)_2$ -Teflon structure. Hydride electrodes are produced in the same manner. This process has the advantages of no pasting, sintering, or drying. In addition, the material has enough strength and integrity that substrates are not needed, offering a significant cost and weight advantage.

These electrodes have always been rolled by hand at EEI, at the rate of about 1 per 30 minutes per person. In order to go into production of 1,000 batteries annually, it would be necessary to roll approximately 300 electrodes per hour. Therefore, EEI must scale-up process rates, while significantly reducing labor. The first iteration of scale-up was to use semi-automatic 6 in rolling machines, where material was rolled back and forth, folding and rotating throughout, gradually reducing the gap width. Cells were made utilizing this rolled material to verify performance.

Due to the non-spherical and larger particle size, the hydride electrodes could not be rolled using the above procedure. A similar procedure however, was developed utilizing 1in. rollers to pre-work the material, and then doing the final rolling with the large 6 in. rollers. Cells were also made to verify this process.

This first scale-up was an improvement, and reduced labor, although was far from the necessary output. The next generation of scale-up was to develop a process that could produce electrodes continuously. The process, under consideration for patent, calls for large scale mixing, then pre-working the material, and then rolling it down to final sizes and dimensions. The process facilitates continuous single machine direction rolling with dry materials. EEI believes this process can provide a very low manufacturing cost similar to those found in automotive batteries. Cells were built to verify this process.

Cell Lamination and Sealing Process

Another advantage of the bipolar design is current passes through the cells vertically in a very short path, reducing loses due to inter-cell connections. To do this, foil current collectors directly contact each electrode. The collectors are laminated to a plastic film with cut out contact points. The film overlaps the collectors, enabling it to be sealed, resulting in completely sealed individual cells.

The lamination, done at EEI, applies tar to the die-cut foil, bonds the plastic film to the tar, and finally cleans the tar from the contact points. This is a timely and laborious process. To scale-up for aircraft production, it is necessary to produce 600 laminates per hour. Various concepts were attempted including masking the tar from the contact points on the foil and using pre-tarred foil. EEI also worked with vendors to develop an automated process to make finished laminates, which would include die cutting roll stock foil and film, and laminating them together using EEI's tar. The process is similar to that in the label industry. Test cells verified all processes investigated.

Perhaps the most critical part of EEI's battery is the cell seal. If the seal is not strong enough, leaks will occur ultimately damaging the battery. EEI has developed a reliable sealing technique that was shown to withstand the harsh battery exposure environment. The initial design used a heat seal, which proved to be reliable, although limited in production. As a result, ultrasonic sealing was investigated. This was a continuous sealing technique that could be scaled-up to desired production rates. In addition, ultrasonic sealing resulted in a reduced seal thickness of 0.0035", compared to 0.25" with heat sealing. This results in reduced weight, and increased heat transferability. One seal per cell side gave the same reliability as two seals per cell side with heat sealing. Cells tests verified seal integrity.

Results and Discussions

$Ni(OH)_2$ Electroless Ni Coating Process

EEI's $Ni(OH)_2$ coating process was successfully scaled up to the 10 kg batch level, with no effect on the material performance. Performance is based on the utilization (Actual Ah/Theoretical Ah) of the material tested in cells. Table 1 shows the utilization data of a 10 kg batch compared to a 2 kg batch. Utilization of each process is within 1% of each other. It was observed however, that there is 2 to 3% decrease in utilization when drying by convection vs. vacuum oven.

Cell Number	Batch Number	Batch Size	Theor. Ah	Actual Ah	Utilization
NC309a	EEI-114B	10 kg Batch	1.92	1.92	100%
NC309b	EEI-114B		1.92	1.92	100%
NC317a	P296A	2 kg Batch	1.92	1.91	99%
NC317b	P296A		1.94	1.91	98%

Table 1: Utilization of $Ni(OH)_2$ Plating Batches

It was determined that it is possible to eliminate the initial two activation steps from the process. This is possible by adding the $PdCl_2$ activator directly to the plating bath. The reaction then proceeds as it does using the three-step process. In addition, it was determined that the $PdCl_2$ quantity can be reduced to 70% of the original formula. There was no effect on performance observed when implementing these improvements. Table 2 shows the utilization data from 200 g batches of the 1-step process with reduced $PdCl_2$ compared to the 3-step process.

Cell Number	Batch Number	Batch Parameters	Theor. Ah	Actual Ah	Utilization
NC192a	Test-008	Std. 3-Step Process	1.94	1.87	96%
NC192b	Test-008		1.94	1.88	97%
NC206a	Test-020	1-Step Process, Reduced Activator	1.92	1.85	96%
NC206b	Test-020		1.94	1.85	97%

Table 2: Utilization of 200 g $Ni(OH)_2$ Plating Batches

EEI has proven that the process can be scaled-up and modified to make it ready for manufacturing. The 1-step formula enables process time reduction and semi-continuous operation. Additionally, the reduced activator quantity saves approximately 10% materials cost. EEI believes the process can be scaled up to batches greater than 100 kg, at 1 batch per hour. Still, the drying technique and time must be further improved.

Electrode Rolling Processes

EEI successfully proved that nickel and hydride electrode rolling can be scaled-up using semi-automatic rolling machines. Multiple cells have been built using these techniques, with no effect on the performance. These improvements have enabled EEI to modestly scale-up from one 6” x 6” electrode per hour to four 6” x 6” nickel and two 6” x 6” hydride electrodes per hour.

The limiting factor in scaling up a dry electrode rolling process is that the material must be turned and folded to improve the strength. EEI has proven that dry electrodes can be rolled in only one direction providing that sufficient material pre-work is done. This allows the electrodes to be produced in a semi-continuous or continuous process. Test electrodes verified sufficient strength with no performance degradation.

These developments will enable EEI to produce the necessary quantity of electrodes for the military aircraft industry and to compete for a share in commercial applications.

Cell Lamination and Sealing Process

Through discussions with vendors from the converting industry, EEI determined it is possible to produce laminates in high volumes with automated machinery. The lamination concept is similar to that used in the label industry. Samples were tested using these production methods, and resulted in completely sealed cells. A process utilizing this method has the ability to be scaled up to high production rates. The process utilizes a rolling system to apply the tar to foil, and then laminate it to the film. Pre-tarred foil is also a viable option to an initial scale-up, although results in an unwanted release paper. Masking of the contact points when applying the tar was not a viable option to facilitate the lamination process.

EEI has proven that cells can be individually sealed using ultrasonic welding. A continuous ultrasonic welder provided a highly reliable seal. Cells tested under a broad range of conditions, ranging from -40 °C to 85 °C, overcharging, and vibration testing, maintained the seal integrity throughout testing. In addition, the continuous ultrasonic sealing process can be implemented into a cell assembly line for increased production in a continuous process.

Conclusions

1. EEI’s nickel hydroxide coating process is a scalable process, that could be further improved for large-scale production
2. EEI has developed a concept to continuously roll plastic-bonded dry electrodes for the bipolar nickel-metal hydride battery.
3. The cell packaging lamination process can be scaled-up using a concept similar to that used in the label industry.
4. EEI’s ultrasonic sealing provides a reliable and producible process for obtaining completely sealed cells.

Acknowledgments

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