Commercialization of Fuel Cell Bipolar Plate Manufacturing by Electromagnetic Forming *

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Abstract

The cost of manufacturing bipolar plates is a major component to the overall cost structure of a Proton Exchange Membrane (PEM) fuel cell stack. To achieve the commercialization of PEM fuel cells, a high volume and low cost manufacturing process for the bipolar plate must be developed. American Trim has identified high velocity electromagnetic forming as a suitable technology to manufacture metallic fuel cell bipolar plates, because of its low capital cost, flexible tooling and rapid prototyping capability. Through the support from the State of Ohio Third Frontier Fuel Cell Program, a group of collaborators consisting of American Trim, The Ohio State University and General Motors have developed a commercially viable prototype production process to manufacture metallic fuel cell bipolar plates in which electromagnetic coils and forming dies were integrated.

To manufacture fuel cell bipolar plates, a metal sheet is accelerated by electromagnetic force to impact against, and take the shape of, the forming die surface. A novel approach which introduces a compliant layer eliminates the need for expendable driver plates in order to reduce the production cost. This process enables continuous manufacturing of fuel cell bipolar plates in short-time cycles at very low cost, which demonstrates strong potential for commercialization.

This paper will introduce the electromagnetic forming process developed to manufacture metallic bipolar plates, and include a discussion of the preliminary results. The benefits of using this high velocity electromagnetic forming process over a traditional stamping press will also be discussed. To commercialize electromagnetic forming, coil life and die wear are being investigated. The results of some preliminary experiments involving coil durability and die wear will also be presented.

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Keywords

Manufacturing, Sheet metal, Simulation

1 Introduction

Proton Exchange Membrane (PEM) fuel cells use hydrogen fuel and oxygen from the air to produce electricity, which is one of the most promising power sources in the near future to reduce our dependence on oil and lower harmful emissions [1]. A key component of PEM fuel cells is the bipolar plate, which separates reactant and coolant from one another. Each bipolar plate assembly has two plates known as the cathode and anode, which must be produced separately and joined together later. A fuel cell stack consists of about 500 bipolar plate assemblies. The volume requirements for PEM bipolar fuel cell plates are potentially very large.

The biggest barrier to PEM fuel cells becoming a mainstream technology is their cost. To reduce cost, each component of PEM fuel cells must be analyzed for cost savings potential. One study estimates that the bipolar plates make up about 41% of the cost of a typical PEM fuel cell stack, and the stack is the most costly part of the fuel cell system, at about 42% of the total system cost [2]. Therefore, to achieve the commercialization of PEM fuel cells, the cost of PEM fuel cell bipolar plates must be reduced, and a high volume and low cost manufacturing process for the bipolar plates must be developed.

American Trim, The Ohio State University and General Motors have developed a novel process to manufacture metallic PEM fuel cell bipolar plate by electromagnetic forming. The prototype manufacturing machine has been made, which proves this process is commercially viable. This paper will introduce the principles and the preliminary results of this manufacturing process, and also present the experiment results of the investigation on coil durability and die wear.

2 Background

2.1 Requirements for PEM Fuel Cell Bipolar Plates

PEM fuel cell bipolar plates need significant mechanical strength to maintain clamping forces without leaking. The serpentine channels on the face of plates should be deep and narrow to optimize fuel cell efficiency. Besides, the plates should be relatively thin to minimize mass. Therefore, the functional requirements for the bipolar plates are: (1) strong, light, thin; (2) corrosion resistant; (3) joinable; and (4) formable into complex shapes.

Currently, graphite composites draw lots of interests for PEM bipolar plate manufacturing for their low surface contact resistance and high corrosion resistance. But metals have higher durability to shock and vibration, and are more suitable for high volume and low cost manufacturing, when compared to graphite composites [3]. Among metals, stainless steels are considered as good candidate materials because of their high mechanical strength, good formability, easy manufacturability for complex shapes, corrosion resistance, weldability and low cost. Therefore, in this development, stainless steel was chosen for bipolar plate manufacturing.

2.2 Possible Forming Methods

There are several methods that can be used to manufacture metallic bipolar plates: machining, hydro-forming, conventional stamping and high velocity electromagnetic forming. Machining bipolar plates from metal block has low production rate and much waste. Compared to hydro-forming, conventional stamping is more capable of high production rate required for high volume and low cost manufacturing process.

Electromagnetic forming is usually applied to accelerate metal sheet to high velocity at a very short period by non-contact electromagnetic forces. During electromagnetic forming, a large electric current pulse passes through a conductive coil by discharging a capacitor bank. The current pulse produces a transient magnetic field around the coil, which induces eddy currents in a nearby metal workpiece. Mutually repulsive forces between the stationary coil and the metal sheet cause the metal sheet to be accelerated toward and impact upon a nearby die surface at very high velocity.

Compared to conventional stamping, electromagnetic forming offers several advantages. First, only single-sided tooling is required, as opposed to a precisely machined matched punch and die set. As shown in Figure 1, the metal sheet impacts a tool only on one side and the other side only receives magnetic pressure [4]. Therefore, tooling cost and complexity are significantly reduced, and the need for precision alignment of upper and lower tools is eliminated. Furthermore, die changes and die modifications are greatly simplified.

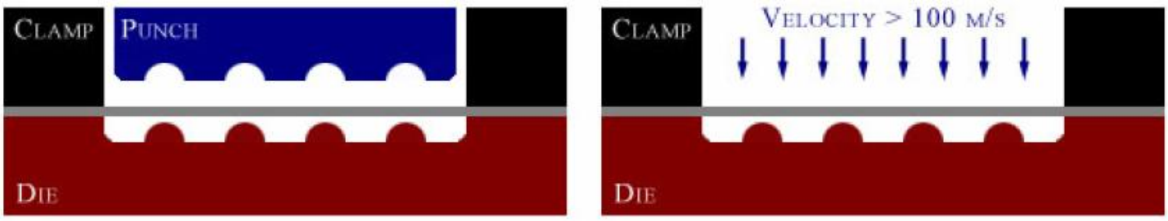

***Figure 1**: Schematic illustrations of conventional stamping (left) and electromagnetic forming (right) [4]*

The second advantage is that much lighter tooling and fixtures can be used in electromagnetic forming. In electromagnetic forming, the large pressure is generated only during high velocity impact between die and metal sheet. Therefore, the tooling and supports need only be sufficient to accelerate and decelerate a metal sheet, which typically has a low mass. The overall forming system can be a fraction of the size used in conventional press systems.

The third advantage is the improved formability. Electromagnetic forming is characterized by very high material velocity and deformation strain rates, which makes it fundamentally different from conventional sheet metal forming. At sufficiently high velocities and/or strain rates, stretching limits are not bounded by the restrictions of a traditional Forming Limit Diagram (FLD). Instead, ductility far beyond typical quasi-static forming limits can be achieved [5, 6]. Therefore, high velocity electromagnetic forming has the potential to improve material formability, and thus to expand the range of candidate materials for a particular application.

2.3 Compliant Layer Electromagnetic Forming

Manufacturing bipolar plate from stainless steel sheet by electromagnetic forming has two major challenges. The first challenge is the low electrical conductivity of stainless steel. Electromagnetic forming has high efficiency for metals with high electrical conductivity, such as Cu, Al alloys. For stainless steel, a secondary driver sheet/plate is needed to generate enough repulsive electromagnetic forces and drive stainless steel sheet to high velocity. This kind of driver plate is usually made of metals with high conductivity and placed between coil and metal sheet. The second challenge is the uniform pressure requirement for bipolar plate manufacturing. Bipolar plate has serpentine channels around the whole parts. This requires the whole stainless steel sheet impact onto the forming die at the same velocity, which needs the uniformly distributed forces on the whole sheet.

The flat spiral coil has a point without magnetic pressure at the center and can not directly provide a uniform pressure on the whole metal sheet [7]. The uniform pressure actuator developed in the Ohio State University can efficiently generate a uniform pressure on the entire metal sheet [7]. But for stainless steel bipolar plates, the uniform pressure actuator demands a thin driver sheet that impacts the forming die together with stainless steel sheet and then deforms together. This deformed driver sheet can not be reusable, which increases the manufacturing cost. American Trim developed a novel approach, compliant layer electromagnetic forming, to eliminate the need for expendable driver plates and also to enable the stainless steel sheet impact the forming die at the same velocity. Figure 2 is the schematic diagram illustrating this approach.

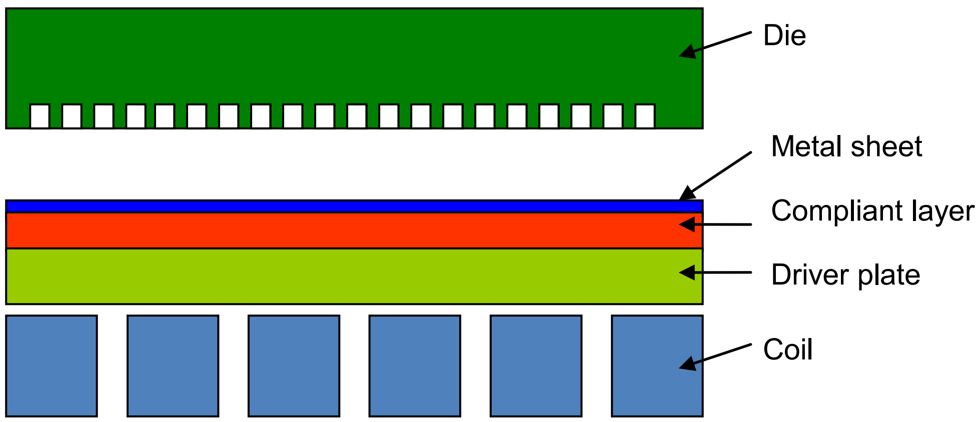

***Figure 2**: Schematic diagram of complaint layer electromagnetic forming*

In compliant layer electromagnetic forming, a thick driver plate made of high conductivity metal is positioned next to the flat spiral coil that is specifically designed according to the size of bipolar plate. A compliant layer made of elastomer materials such as urethane is placed between the driver plate and the stainless steel sheet. The forming die is above the steel sheet and there is a short distance between them. Upon discharge of the capacitor bank, the primary current in the spiral coil and the induced eddy currents in the driver plate produce the repulsive Lorenz force, which accelerates the driver plate together with compliant layer and stainless steel sheet to impact the forming die at high velocity. The compliant layer presses the stainless steel sheet into the die cavity, and also reduces the impact on the driver plate. After impact, the stainless steel sheet is formed to produce a bipolar plate. The driver plate and compliant layer retain their original shape and are ready for the next forming operation.

3 Commercialization of PEM Fuel Cell Plate Manufacturing

3.1 Prototype Machine for PEM Fuel Cell Plate Manufacturing

As described before, the potential volume requirements for bipolar plates are very large, which requires the automation of manufacturing process to improve the production rate. Compliant layer electromagnetic forming needs only single-sided tooling which remains stationary during the manufacturing process. This simplifies many aspects of the forming process, and eliminates considerations such as the alignment of matched tool sets, which makes it easy to apply automation for the manufacturing process. Figure 3 is the automation concept of bipolar plate manufacturing by electromagnetic forming. During the production, the stainless steel strip is fed continuously from one strip coil to the other strip coil, passing horizontally through the electromagnetic forming system that consists of capacitor bank, electromagnetic coil and forming die. In capacitor bank discharging, the strip stops, and the section of the strip between the coil and the forming die is deformed into a bipolar plate by electromagnetic forming. Then the deformed section moves away horizontally along the fixture, and another section of the strip moves in for next forming.

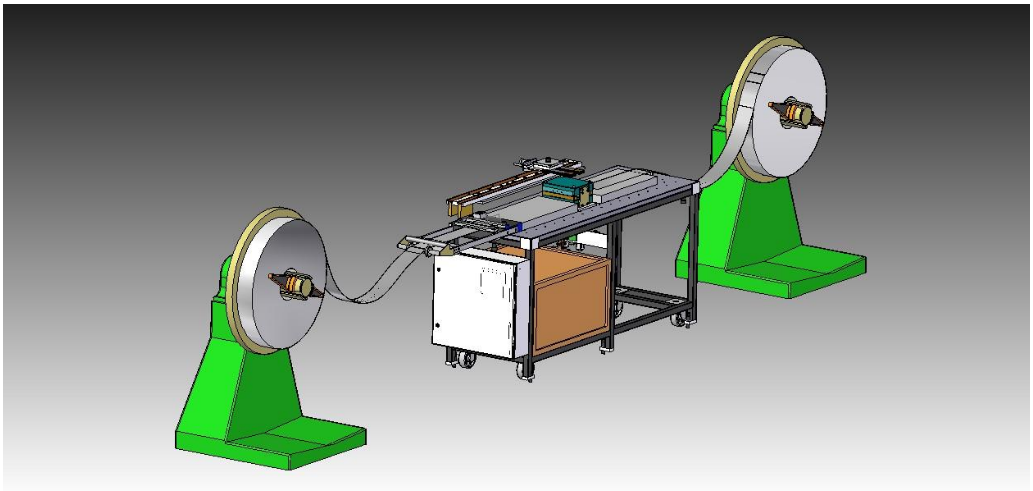

***Figure 3**: Automation concept of bipolar plate manufacturing by electromagnetic forming*

Based on the automation concept in Figure 3, American Trim has developed the prototype machine for sub-sized bipolar plate manufacturing by compliant layer electromagnetic forming. Figure 4 shows the photo of this prototype machine. In this machine, a capacitor bank is located in the left lower corner of the frame. And the flat spiral coil, the thick driver plate, the compliant layer and the forming die are placed at the upside section of the frame. The strip horizontal movement and the capacitor discharging can be all programmed to speed up the process. Using this prototype machine, the production rate reaches 5 seconds per plate, which demonstrates the commercial viability of this manufacturing process. Figure 5 is the bipolar plate strip formed by the prototype machine.

***Figure 4**: Prototype machine for bipolar plate manufacturing by compliant layer electromagnetic forming*

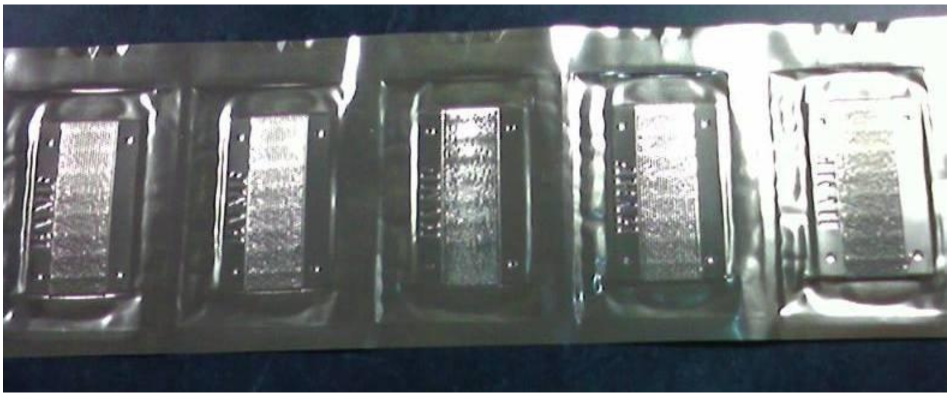

***Figure 5**: Bipolar plate strip formed by the prototype machine*

3.2 Preliminary Results

Compliant layer electromagnetic forming was applied to manufacture sub-sized bipolar plate. Figure 6 is the photo of the forming die used in bipolar plate manufacturing. The size of the die is 78.5mm x 63 mm. Figure 7 is the laser scan profile of the forming die along X line shown in Figure 6. The channel depth of the forming die was measured as 311 μm. Using this die and the compliant layer approach, a ferritic stainless steel 439 sheet with 0.1 mm thickness was deformed at 9 kJ energy input. Figure 8 is the laser scan profile of the formed bipolar plate along X line. The channel depth was measured as 260 μm, and reaches 87% of the channel depth of the forming die.

The energy input has large effect on the channel depth of the formed parts. The higher the energy input, the deeper the channel depth of the formed parts can reach. In the future experiments, an energy input larger than 9 kJ is planed to apply, in order to improve the channel depth.

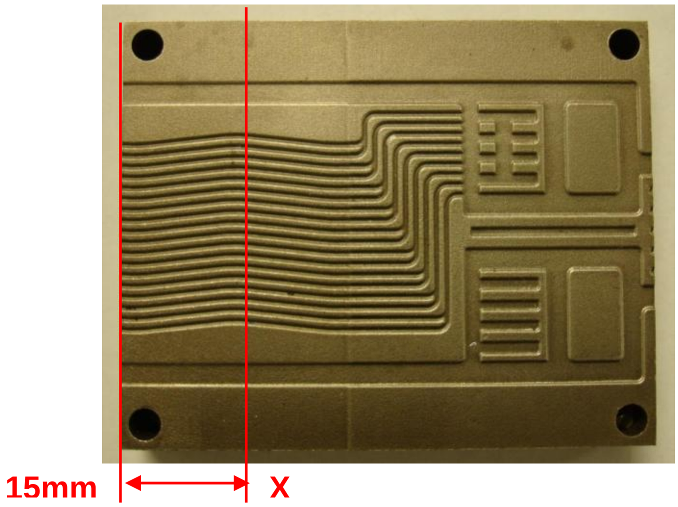

***Figure 6**: Photo of the forming die used in bipolar plate manufacturing (size: 78.5mm x 63mm)*

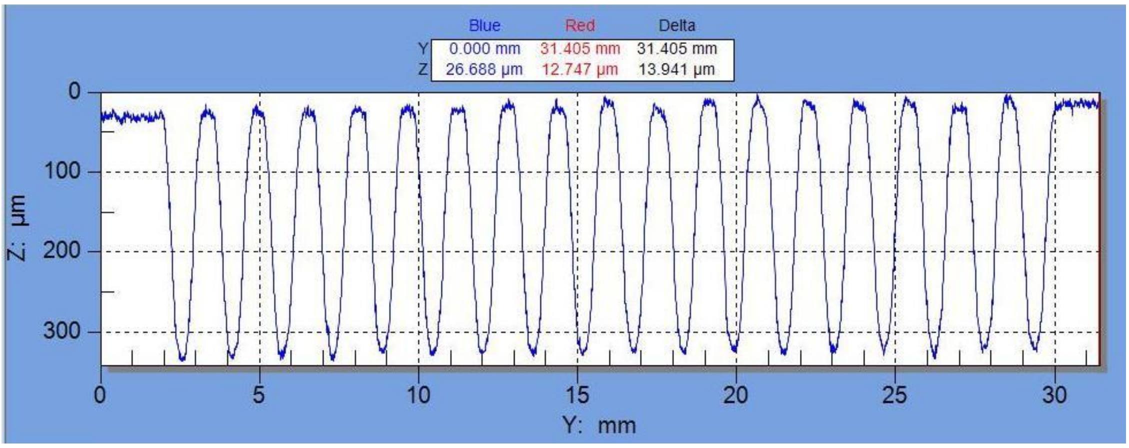

***Figure 7**: Laser scan profile of the forming die used in bipolar plate manufacturing*

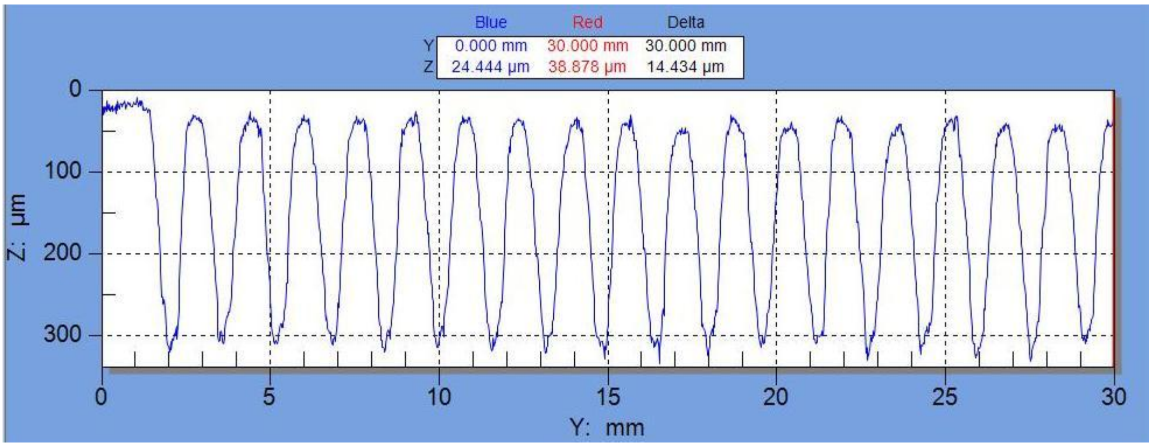

***Figure 8**: Laser scan profile of the formed bipolar plate by compliant layer electromagnetic forming (439SS with 0.1 mm thickness and 9 kJ energy input)*

3.3 Coil Durability and Die Wear

Besides of the production rate, the durability of forming system is important to the production cost and the commercialization of bipolar plate manufacturing. The electromagnetic coil and the forming die are two major components in the forming system. And their durability was investigated in this development.

During electromagnetic forming, repulsive forces are applied on the spiral coil and cause the coil to rebound from its initial position. Large deflections will reduce the coil life and affect the electromagnetic forces on the driver plate. The flat spiral Cu coil was applied in the compliant layer electromagnetic forming. The coil was embedded into a G10 Garolite block, and covered with a 1.0mm thick G10 Garolite sheet that serves as the insulation between the coil and the metal driver plate. Initially, the thin G10 sheet was flat. After over 500 electromagnetic forming operations, the flatness of the G10 sheet was checked by laser scanning along Y line shown in Figure 9. Figure 9 indicates that the maximum deflection is 0.24 mm, which is insignificant compared to the coil size (the coil thickness is 12.5 mm).

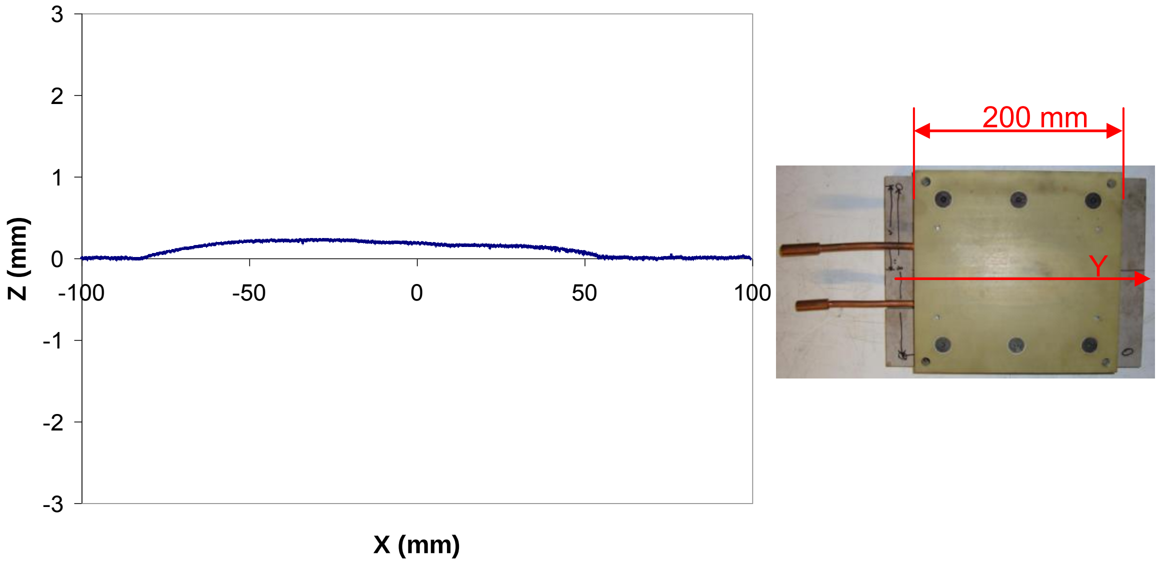

***Figure 9**: Laser scan profile of the top of the flat spiral coil along Y line after 500 hits*

For the forming die, the high velocity impact of stainless steel sheet onto the die will cause the die wear. Considerable die wear will make the dimension of bipolar plate inaccurate. In this development, the forming die was made of A2 tool steel. To investigate the die wear, the forming die was scanned by the laser profilometer before and after over 500 times of impact. Figure 10 is the comparison of the scanning results, which shows that there is no significant difference between these two scan profiles.

Above results indicate that there are no significant changes in the flat spiral coil and the forming die after over 500 electromagnetic forming operations. Therefore, the durability of the coil and the die wear are sufficient to commercialize the bipolar plate manufacturing.

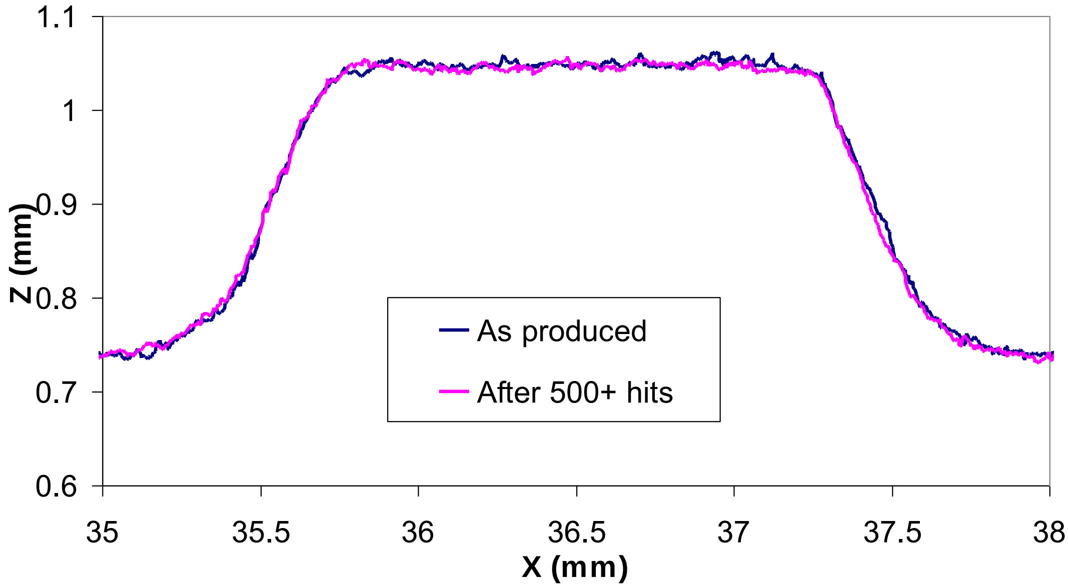

***Figure 10**: Comparison of laser scan profiles of one channel of the forming die*

3.4 Challenges of Electromagnetic Forming Commercialization

Overall, the preliminary manufacturing results and the durability investigation are encouraging. But there are still several challenges for the commercialization of bipolar plate manufacturing by electromagnetic forming.

(1) The prototype machine can be used to form the sub-sized bipolar plates. The process has to be scaled up for full scale bipolar plate manufacturing.

(2) More work is needed to improve the channel depth of the formed parts to reach the target channel depth, which includes the optimization of energy input, compliant layer properties, coil design, driver plate geometry and distance between stainless steel sheet and the forming die.

(3) Higher energy input and more electromagnetic forming operations are needed for the durability study on coil life, die wear and compliant layer life.

(4) Thermal management for the coil and the driver plate should be investigated, since the large currents in the coil and the driver plate generate resistance heat and then cause their temperatures increase.

4 Summary

A novel process, compliant layer electromagnetic forming, has been developed in American Trim to manufacture the PEM fuel cell bipolar plate. In this process, elastomer compliant layer and thick driver plate are introduced to eliminate the need for expendable driver plate and to accelerate the metal sheet to high velocity. A prototype machine was successfully developed to manufacture sub-sized PEM fuel cell bipolar plate by this process. By 9 kJ energy input, the channel depth reached 87% of the target channel depth. In addition, the 5-second cycle time was achieved using the prototype machine. The durability investigation shows that the coil life and the die wear are sufficient to commercialize the bipolar plate manufacturing process.

The preliminary results are encouraging, and demonstrate the above bipolar plate manufacturing process is commercially viable. To commercialize the full scale bipolar plate manufacturing, further development is required.

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