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A study of the surface roughness of the Nafion membrane in a PEM fuel cell

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Abstract

Polymer Electrolyte Membrane/Proton Exchange Membrane (PEM) fuel cells operate utilizing electrochemical reactions which take place on a surface. This work sets out to test the hypothesis, that increasing area due to greater roughness will increase the power output density. Nafion membranes were molded using heated aluminum dies, which were ground and machined to produce a variety of surface textures (thereby imprinting the Nafion membrane with the different textures from the molds). The textures of the each Nafion membrane were measured using an Olympus LEXT 3100 scanning laser microscope. Area-scale analysis and scale-based correlation testing were used to determine the extent of correlations between the textures and the power density of the fuel cell and the scale ranges over which correlations exist.

Introduction

Objective

This research identifies the challenges involved with modifying, discriminating, measuring, and calculating the effective area of the Nafion electrode membrane a critical component of the Proton Exchange Membrane or Polymer Electrolyte Membrane (PEM) fuel cell.

As reported by Larminie and Dicks, the two fundamental problems with fuel cells other than costs are hydrogen not being a readily available fuel source and low power and current outputs of fuel cells. One of the main factors of the low current output is the electrode area (Larminie & Dicks, 2003). As the area of the electrode increases the current and power output increases. Since the reaction that drives the fuel cell occurs over a surface area, this research is setting out to analyze the hypothesis that by modifying the surface texture, the surface area of the

the Nafion membrane of the PEM fuel cell will increase, and therefore will result in an increase of the performance of the fuel cell reflected by the current and power outputs of the fuel cell.

By analyzing the performance of the fuel cell using the membranes with modified surface texture we hope to be able to determine at which scale the chemical reaction occurs.

Rationale

What is a fuel cell?

A fuel cell is similar to a battery because it takes chemical energy and converts it directly into electrical energy. Unlike a battery which has a fixed amount of stored energy, a fuel cell will continue to operate as long as the fuel, hydrogen, is supplied. Fuel cell technology shows great promise for a variety of reasons including but not limited to high efficiency, high reliability, low noise pollution, and they are environmentally friendly. Fuel cells are part of the solution to the Earth's energy crisis.

PEM fuel cell

There are many different types of fuel cells. This research as state previously focuses on the Proton Exchange Membrane fuel cells or Polymer Electrolyte Membrane fuel cells are two names referring to the same thing. PEM fuel cells are low temperature, low power output fuel cells. Applications for PEM fuel cells range from space exploration to use in portable electronics. There are many benefits unique to PEM fuel cells that make them suitable for consumer use. Advantages such as the short start up time, the ability to be cycled on and off many times, they operate at low temperatures of about 70C to 100C, PEM fuel cells are stable, easy fabrication, and easy to opperate (Jung, et al., 2007). These possible applications and advantages create drive for increased research on the PEM fuel cell.

All fuel cells contain four main stack components, the current collector, the catalyst, electrode, and end plates. Specifically with in the last 30 years much research has been conducted on all of these components. This study looks specifically at the Nafion electrode membrane of the PEM fuel cell. The electrode in the fuel cell acts as a permeable ionic membrane, allowing hydrogen ions to pass through from the anode to the cathode. Nafion is the most promising commercially available polymer electrode available for use in PEMs and Nafion place a crucial role in ion transportation (Choi, Jalani, & Datta, 2005). Stumper, Campbell, Wilkinson, Johnson, and Davis agree that in order to achieve the optimum performance of the electrochemical reaction, the whole electrode area is of "prime importance".

State-of-the-art

Many studies involving modification of Nafion membrane inside the fuel cell have been conducted to improve the performance of the fuel cell. These studies include Nafion exposed to ion bombardment, polymer doping, acid doped, precursor impregnation, and Atomic Force Microscope (AFM) tapping measurement.

One method of Nafion surface modification was to use varying argon plasma energies to bombard the surface of the Nafion. The argon plasma energies ranged from 0 to 3.056 $J \cdot cm^{-2}$. The Nafion surfaces were measured using a Scanning Electron Microscope (SEM), AFM, and X-ray Photoelectron Spectroscopy (XPS). Another important characteristic in this study was the water contact angle of the plastic. As the energy of the plasma increased the contact angle of the water decreased from 120° for the unmodified Nafion and 50° for the modified Nafion. The SEM and AFM measurements did not indicate much of an increase in the surface roughness of the Nafion membranes. The modified membranes were then tested in a Direct Methanol Fuel Cell (DMFC). The findings reported poor electrical poor electrical performance from the membranes that were treated with the plasma; this was attributed to the poor contact between the electrode and the pressed Membrane Electrode Assembly (MEA) (Jung, et al., 2007).

Another way of modifying the electrolyte is using a chemically altered electrolyte. Wang, Wainright, Savinell, and Litt tested a new polymer electrolyte membrane made from acid-doped polybenzimidazoles. They tested this membrane, which is chemically different from Nafion, using a DMFC. The polybenzimidazoles was found to increase performance by decreasing methanol fuel crossover (Wang, Wainright, Savinell, & Litt, 1996). Another type of membrane that has been tested is Poly(perfluorosulfonate acid) that has been doped with cesium ions and hydrogen ions. This membrane was also tested in a DMFC and was demonstrated to decrease the methanol crossover thus increasing the power (Tricoli, 1998).

A study by Lehamni, Durand-Vidal, and Turq investigated the surface effects of the Nafion swelling. They used an AFM to measure the surface of the Nafion membrane after being exposed to either nothing (dry), water, or tributylphosphate. The AFM was in the tapping mode for the measurements to reduce the amount of force on the surface of the Nafion. This study did not complete a fuel cell test with the Nafion. The purpose of this experiment gain knowledge about methods of measuring Nafion using the AFM to measure Nafion and characterize the surface roughness parameters (Lehmani, Durand-Vidal, & Turq, 1998).

Approach

As one can see, the polymer membrane electrolyte has been studied quite extensively. This study will use an industry standard membrane Nafion, specifically Nafion 115. This will keep the starting width constant throughout the experiments. The Nafion membrane will be modified using a hot pressing technique to transfer a structure on the aluminum mold. Measurements of the surface of the Nafion will be taken by the Olympus LEXT3100 scanning laser confocal microscope. Instead of using surface roughness parameters as a way to characterize the surface of the modified Nafion as Lehamni, Durand-Vidal, and Turq, this study will use area-scale analysis to compare the relative area as a function of scale. Then fuel cell tests will be conducted using a direct hydrogen PEM fuel cell, whereas most of the previous studies used DMFCs to test the performance of the membranes.

Methods

Molds

When considering how to impart surface textures on the Nafion membrane, a technique similar to the one used to create waffles was employed. When one makes waffles they use a waffle iron with a unique structure on the plates of the waffle iron. The structure that is on the plates of the waffle iron is then imparted from the plates of the iron to the cooked waffle. This resembles the technique used alter the surface of the Nafion. The Nafion has deformed thermoplastically, but may still have memory of its previous shape that it could recover upon reheating where as the waffle does not have this effect.

Mold Surface Selection

When selecting the processes used in creating the molds, it was necessary to use surfaces that had characteristically different areas by area-scale analysis. Since Nafion 115 was used is only 5 thousands of an inch thick or 127 micrometers thick the surfaces of the molds, while rough on a small scale, had to be flat with respect to the large scale in order to create an even pressure during the pressing process. This also allows for a more even texture transfer because if one surface is flat on the large scale and the other surface has high and low points on the large scale the two dies when placed face to face could only contact at a minimum of three points.

With these considerations in mind three processes were chosen to fabricate mold surfaces; milling, turning, and grinding. These methods will provide different surfaces, as well as generate a moderately flat surface.

Mold material selection was important due to the possible transfer of the material from the mold to the Nafion if the metal were to oxidize. This is why aluminum 6061-T6 1.25 in. round was used for the molds. Aluminum provides good resistance to corrosion, and it is an easy metal to machine allowing for many different types of surface finishes to be applied to it.

The first step in preparation of the molds was to take the long bar stock and trim it down to size. The lathe was used to face each mold and then part off the mold at about nine tenths of an inch for the height of each mold. Each surface finish must have two molds of that surface made, one for the top surface of the Nafion and one for the bottom surface of the Nafion.

Molds- Milled

Milled molds were fabricated using a Haas Mini Mill, a Computer Numerical Controlled (CNC) mill. The tool that was used for each milled part was a tri-insert facing mill. The tool feeds and speeds were the variable that changed to create the different surface finishes; Table 1 has the feeds and speed information used for the sets of milled molds. Then a small chamfer was completed to remove the burrs from the edges of the faced surface.

Mold Set	z-feedrate [PM]	xy-feedrate [PM]	Speed [RPM]	Depth of cut [in]
M1	25.305	101.22	3374	0.05
M2	45	180	6000	0.05
M3	45	90	6000	0.05

Table 1 – Feedsrates, Speeds, and Depth of cut for the milled mold sets.

Molds- Turned

Turned molds were fabricated using a Haas SL-20 CNC lathe. The tool that was used to create each part had a tool-nose-radius of 0.8mm. The feed of the tool was varied during the facing operation and the speed was held constant at 2000 surface feet per minute. Table 2 has the feeds used for the sets of turned molds.

Mold Set	Feed [in/rev]
T1	0.006
T2	0.012
T3	0.024

Table 2 Feeds for turned mold sets.

Molds- Ground

The first step as mentioned previously for creation of the ground molds were to be cut to proper length on the Hass SL-20 CNC lathe. A low feed rate was used to create a flat surface that would have low peak to valley roughness to ensure that during the grinding process material removal happened fast and no residual turned marks were left in the ground surface. The purpose behind the short grinding time is so that the surface of die remains flat. When grinding with a rotary polisher the longer the time spent grinding, and the more material removed, the higher the probability of creating a multifaceted surface. Instead of being a single flat surface, the surface would have multiple individually flat surfaces and will result in a poor Nafion modification. The polished surfaces were made using four different grit and two type of abrasives listed in Table 3. The two types of abrasive were fixed abrasive and loose abrasive, suspended in solution.

Mold Set	Abrasive Type	Grit
G1	Loose	1 µm
G2	Permanent	600
G3	Permanent	320
G4	Permanent	60

Table 3 - Types of abrasive and Grit of abrasive used for ground molds

Molding Process

Application of Heat

The first attempt to use heat, to aid in softening the Nafion to making it easier to form, was to submerge the Nafion in water heated to 70°C for two minutes. After a molding attempt was made, the Nafion could not be discriminated visually or by measurement from the unmodified Nafion. A second attempt was made heat the Nafion to modify it using the same process but with 100°C water which yielded the same result. For the third method instead of attempting to heat the Nafion membrane by submerging it in heated water, the molds were heated using an oven. The molds were brought to 250°F or 121.1°C. The molds were taken immediately out of the oven and pressure was applied to the mold. This technique modified the surface texture of the Nafion and was employed for Nafion modification.

Application of Pressure

It was necessary to find out how much pressure to use. The first attempt was to use a clean plate glass surface on the bottom, place the Nafion membrane on the glass surface, then a mold on top of the Nafion membrane. The force used was generated by a drinking glass filled with water. This left no measureable impression on the Nafion.

In the next attempt the same set up was used except the amount of force was increased by using a pair of small Irwin hand clamps. This generated enough force to visually modify the

Nafion in some areas. The force had been increased but was still not large enough. Two more iterations of the same set-up were completed, only using one Irwin clamp, increasing the size of the clamps each time. As the size of the clamps increased the amount of force generated by the clamps increased. The impressions got deeper as the amount of force increased. However, there were still some regions where the Nafion was not being modified.

The next change in the set-up for the impression was made to the bottom surface. Instead of glass, a material that is ridged brittle and would not conform to the shape of the mold, a rubber material was selected that would compress and impart an even pressure. The rubber would allow for more give to high spots on the mold and allowing the low spots to come in contact with the Nafion membrane. This change gave the Nafion an even impression.

Now that the impression on one side was complete was successful it was to be translated to both sides. The design for the one sided Nafion modification could not be easily adapted to the two sided. The new method involved using two molds instead of just one which had been part of the original design. This reintroduced the spotty transfer of the surface texture from the molds to the Nafion membrane. The only solution was to increase the force applied during processing. Instead of using the Irwin clamp to generate the force, a hydraulic press to generate the force. The press used was a two post press that had a gage which was rated for 10,000 lbs of force. Increasing the force fixed the problem with the spotty transfer of the surface texture.

The final method used to imprint the Nafion involved two molds, heated to 250°F placed on either side of the Nafion membrane then 10,000 lbs of force was applied to Nafion membrane to make a successful impression.

Measurement of the surfaces

Through out the molding process it was imperative to see what surface modifications were being done to the Nafion membrane to refine the pressing process. Thanks to the Surface Metrology Laboratory at the Worcester Polytechnic Institute and Olympus, an Olympus LEXT3100 scanning laser confocal microscope was available to use to measure the surfaces of the Nafion and the aluminum molds.

Measurement of the molds

The confocal focal microscope was used to measure the different molds to see if they could be discriminated from one another. Also the measurements of the molds were used to compare how much the surface texture of the mold was successfully transferred to the Nafion through the pressing process. Measurements of the molds were taken using 20x, 50x, and 100x, and no use of zoom.

Measurement of the Nafion membranes

The confocal microscope was also used to measure the Nafion membranes. Since the Nafion membrane was a transparent material one had to be careful not to measure through the Nafion to the surface that was underneath. This was realized when using an index card as a surface to hold the Nafion during the initial measurements and seeing a measurement that looked similar to paper instead of a smooth surface of the Nafion.

When measuring the Nafion under high objectives (20x-100x) the Nafion would heat due to the laser from the microscope. This would cause the Nafion to absorb water and to swell. This swelling of the Nafion caused it to move when being measured. These movements prevent the surface from being measured accurately. A restraint system for the Nafion during measurement was used. The restraint system consisted of an aluminum cylinder with to magnets inside the cylinder, which were mounted flush with the top surface of the cylinder. The Nafion was placed on a note card to prevent the Nafion from contamination. The note card with the Nafion was placed on the top of the aluminum cylinder. Then a washer was placed on top of the Nafion. The washer was attracted to the magnets and the Nafion was secured by the washer being attracted by the magnets.

Fuel Cell Testing

Membrane Electrode Assembly (MEA)

After the each Nafion membrane was pressed and measured, its performance was to be measured in a direct hydrogen fuel cell. The first step of this process was to prepare the MEA. The MEA consists of the electrolyte (Nafion membrane), catalyst, and the Gas Diffusion Layer (GDL) which also acts as the electrode. The electrolyte separates the reactions that are taking place inside the fuel cell. The catalyst is what causes the reaction to take place and in our case it is a platinum based catalyst. The GDL is a carbon cloth that acts as a current collector, or electrode as well as disperses the fuel throughout the cell. The catalyst and the GDL must be added to the Nafion membrane to complete the MEA.

The First step in preparation of the MEA is making the catalyst. The catalyst is prepared using 7.5 mg of 20% Pt on Vulcan, which is a platinum based catalyst supported by carbon. The next step is to add 18 mg of 10% Nafion solution. The final step was to add 3 ml of 200 proof Methanol. The solution was mixed together and at this point the solution looks heterogeneous. Then the catalyst solution was allowed to sonicate for an hour, to make the solution homogeneous. After the hour of sonication the catalyst was applied to the Nafion membrane using a mask to cover the non-active area of the membrane. The catalyst was applied using an air gun to the membrane in many light coats. After the catalyst was applied to both sides of the membrane, the GDL was affixed to the catalyst.

The GDL was applied using two different methods. For the first trial the GDL was hot pressed using 2000 lbs of force and 270 °F. The hot pressing is used to ensure good contact is made between the catalyst and GDL. The second trial the hot pressing of the GDL was eliminated instead the Nafion membrane that had been coated with the catalyst was placed in 70 °C oven for an hour to remove the natural solvents from the Nafion and catalyst. The GDL was just placed on either side of the MEA when the stack was being assembled.

Fuel Cell Tests

After the MEA was completed it was run in a fuel cell test stack using hydrogen as a fuel. The MEA was conditioned over night. Then the fuel cell was tested at different applied voltages and the current output of the cell was recorded.

Results

Surface Texture Transfer

The Olympus LEXT3100 confocal microscope was used to measure the surfaces of the Nafion membrane and the molds used to modify the Nafion membranes. The measurement of the Nafion membrane modified with the T3 mold visually had a significantly lower amount of surface texture than the T3 mold. The images of the mold and the Nafion membrane generated by the Olympus LEXT 3100 from the measurement are shown in Fig. 1.

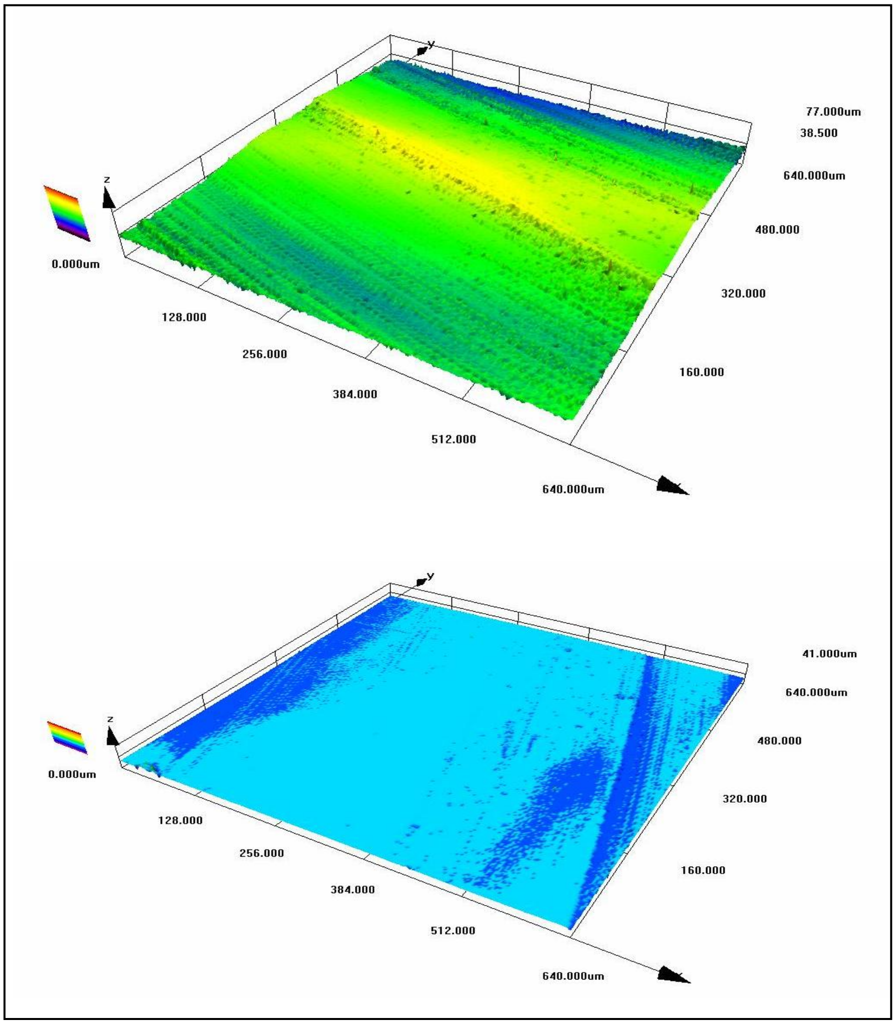

Figure 1 - 3D Images of T3 modified Nafion membrane (lower) and T3 mold (upper) both measured using the 20x objective.

As one can see only a partial transfer of the surface structure from mold T3 to the Nafion membrane occurred. This is shown quantitatively using the methods laid out in the ASME B46 standard using area-scale analysis as shown in Fig. 2. At low scales the mold has relative areas of close to four where as the T3 modified Nafion membrane only has relative areas of 1.33 at low scales. Using area-scale analysis there is an evident discrimination between theT3 modified Nafion membrane and the T3 mold.

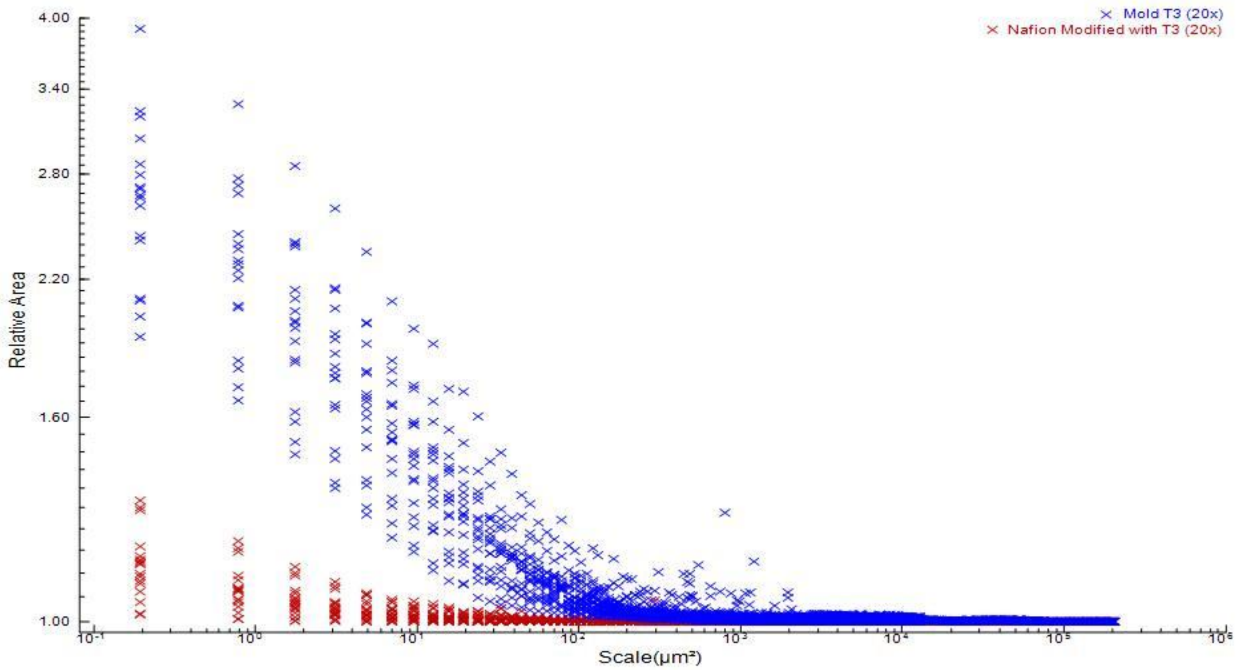

Figure 2 - Area-scale analysis comparison of the surface of theT3 modified Nafion membrane and turned surface of mold T3 (measurements pictured above in Fig. 1)

Confocal Microscope Objectives

The Olympus LEXT3100 confocal microscope has multiple objective lenses (5x, 10x, 20x, 50x and 100x) available for use. Olympus recommends using the higher(50x and 100x) objectives for three dimensional imaging for best results. This reason for this became evident comparing and contrasting images and measurements generated by the microscope. When the lower objective lenses are used to measure surfaces which have significant steep features, which appear as cliffs in the measurement and will be referred to as cliffs, have significantly more large spikes appear near the cliffs using the lower objective lenses than measurements taken using the higher objective lenses. Also low objective lenses can have areas in the image with many small spikes as shown in the 20x objective lens measurement of the T3 mold as portrayed in Fig. 3. This is compared with the 100x measurement, also of the T3 mold, the small spikes that were on the image of the 20x measurement are not seen on the 100x measurement. Area-scale analysis of the 20x and 100x objective lens measurements(Fig. 4) of mold T3 displays a significant discrepancy in the two relative areas calculated for the same surfaces.

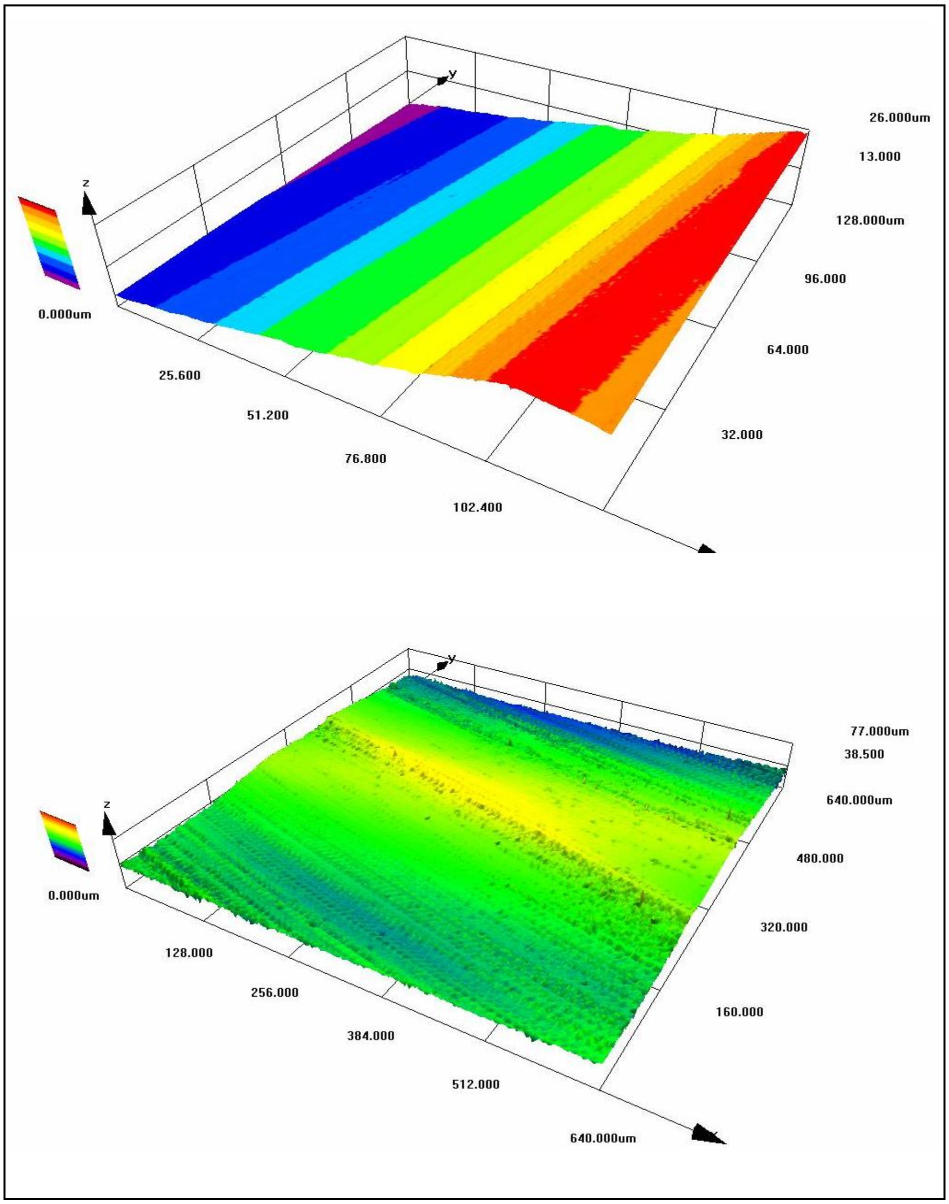

Figure 3 - Mold T3 measurements from an Olympus LEXT3100 using the 20x objective lens(bottom) and the 100x objective lens(top).

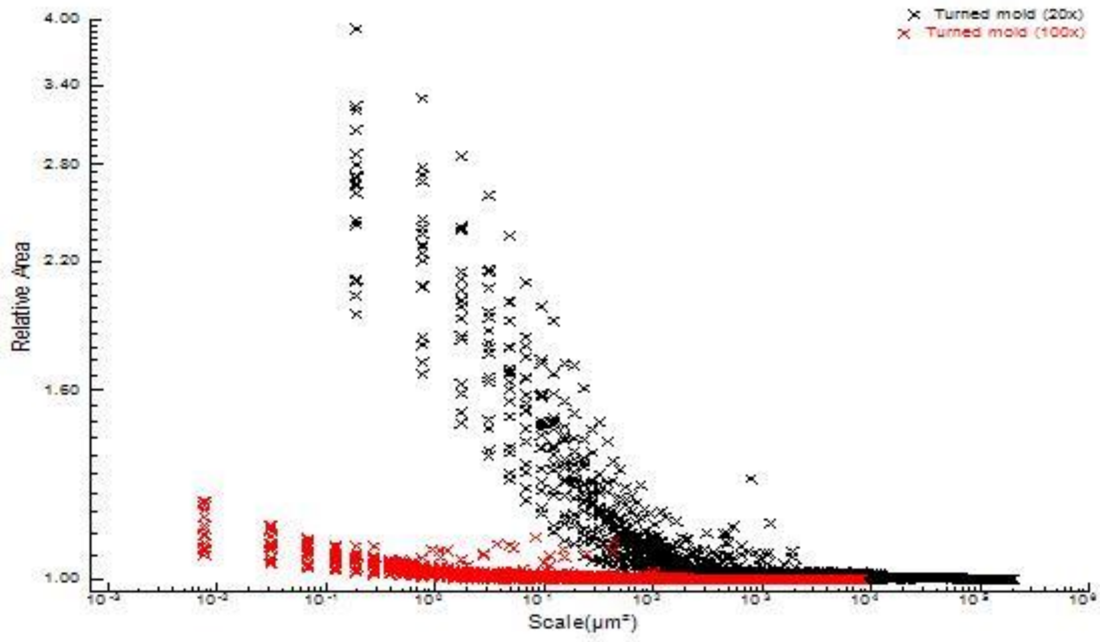

Figure 4 - Area-scale analysis of measurements of mold T3 taken with the Olympus LEXT3100 using the 20x and 100x objective lenses.

Discrimination of Modified Nafion Membranes

The tested modified Nafion membranes were molded using molds G1 and T3. These were the smoothest and the roughest surface textures transferred to the Nafion membrane. These surfaces were discriminated by the area-scale analysis results shown in Fig. 5. The discrimination of the surfaces was not evident simply by looking at the area-scale results; however an F-test of 90% confidence was performed on the area scale results indicating that the surfaces can be distinguished at the micrometer scale as demonstrated by Fig. 6. The inscribed region indicates the point at which the scale of the area-scale analysis is small enough the relative area of the two surfaces can be discriminated with a 90% confidence.

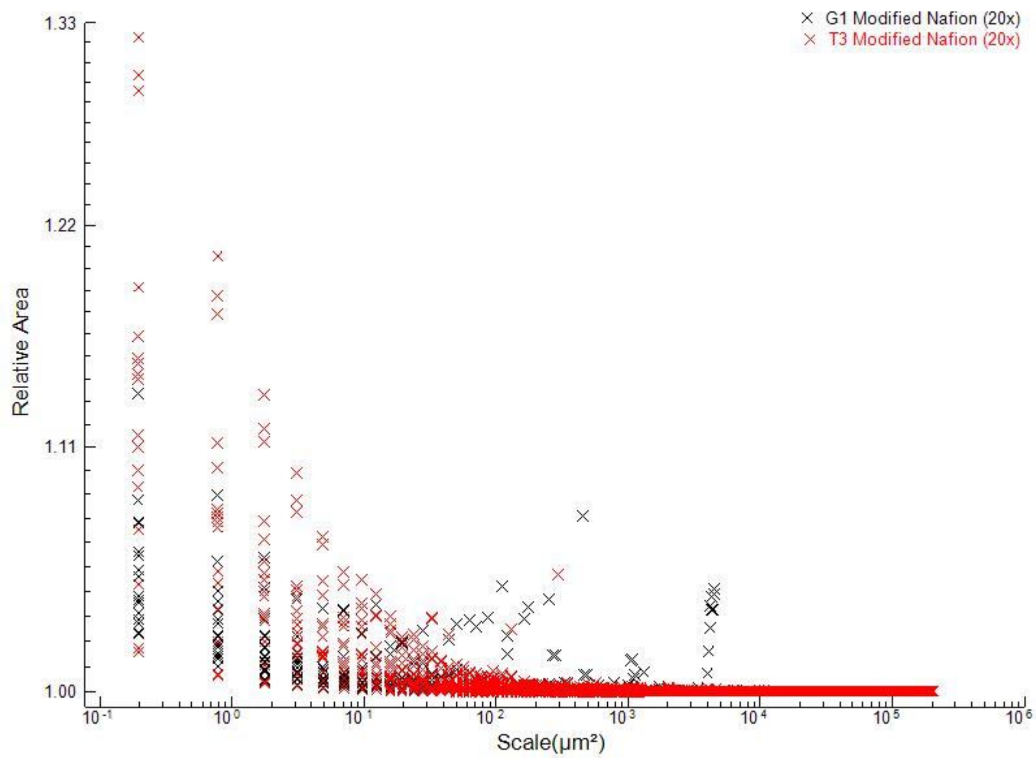

Figure 5 - Area-scale analysis of Nafion membranes modified by molds G1 and T3.

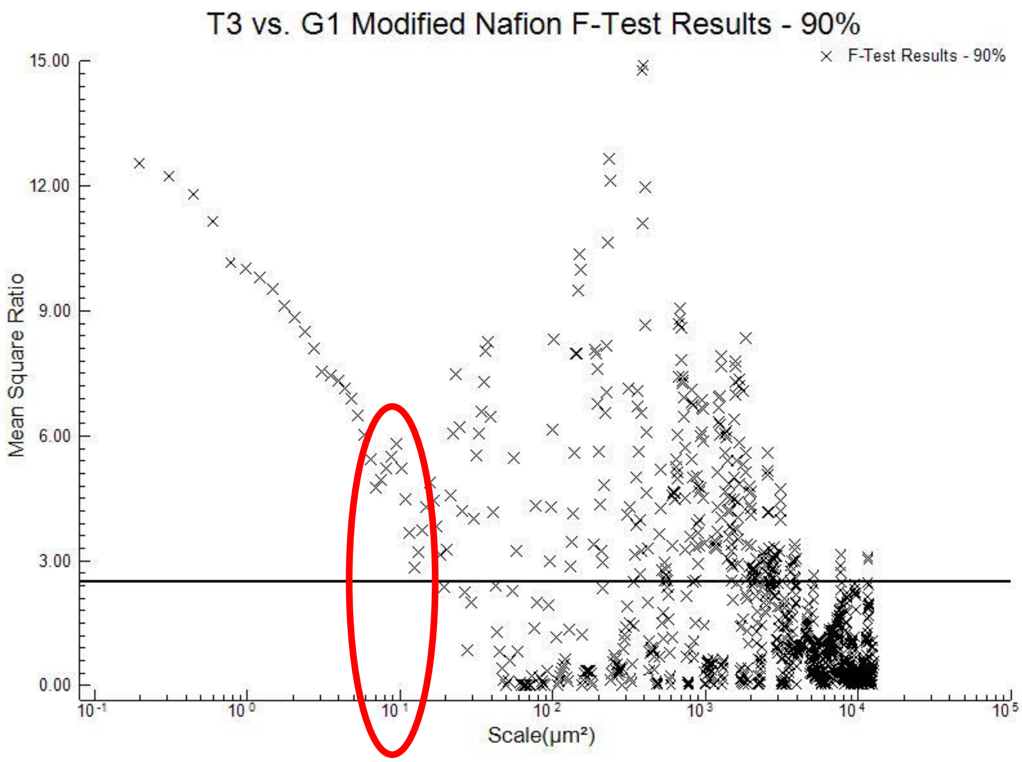

Figure 6 - F-test results of the G1 modified Nafion membrane vs. T3 modified Nafion membrane.

Fuel Cell Test Results

The theory being tested is as the relative area of the Nafion membrane increases, due to an increase in surface structure, a performance increase is hypothesized. The T3 molded Nafion membrane has about a 13% increase in relative area over the G1 molded Nafion as shown from Fig. 5. The performance results from the fuel cells are represented in a graph(Fig. 7). Table 3 explains processes MEAs were subjected to.

MEA 1	Hot Pressed GDL	G1
MEA 2	Hot Pressed GDL	T3
MEA 3	Not Hot Pressed GDL	G1
MEA 4	Not Hot Pressed GDL	T3

Table 4 - MEA labels.

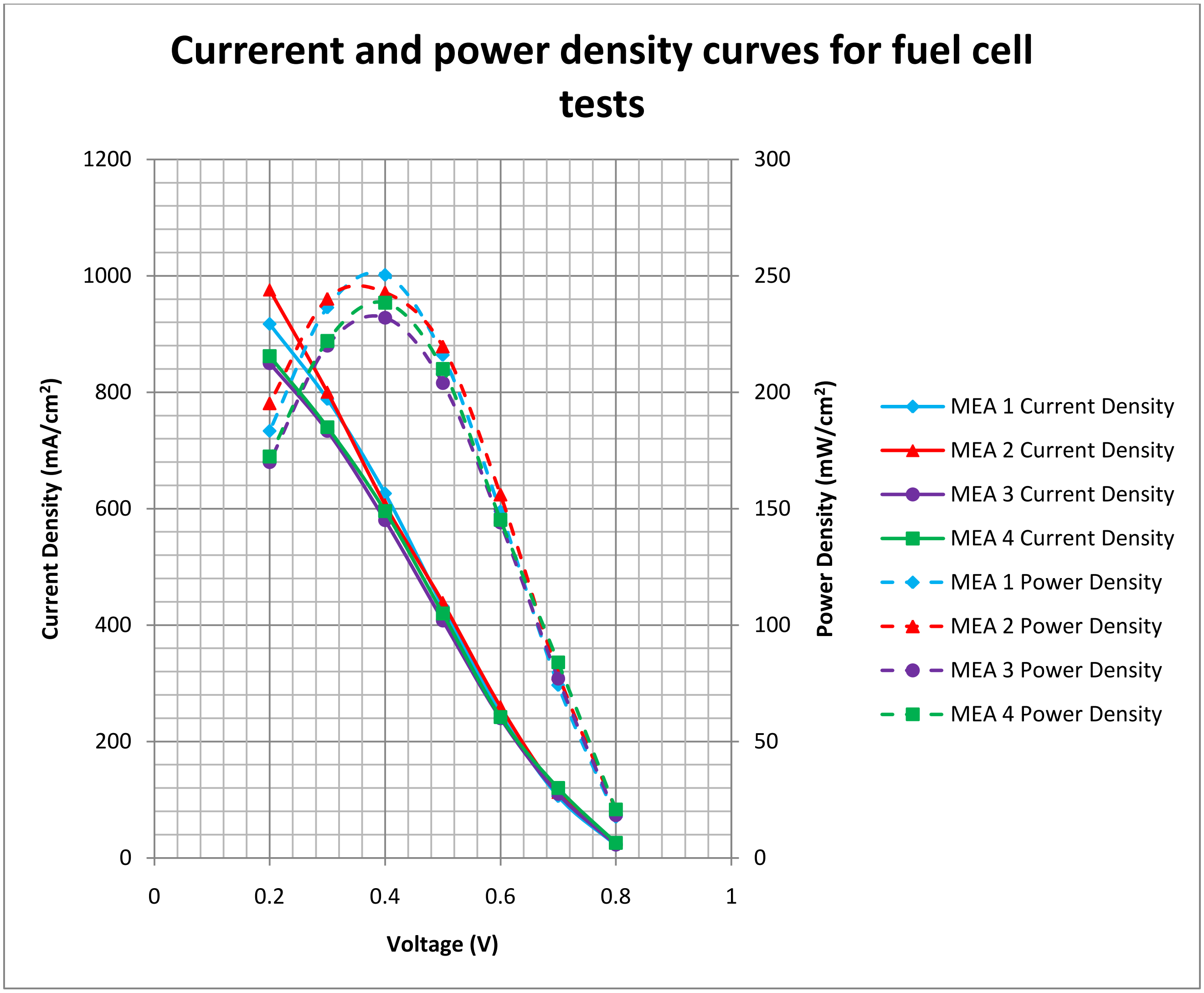

Figure 7 - Fuel Cell Test Results

Discussion

Surface Texture Transfer

Simply by visual inspection of the measurement images (Fig. 1) of the T3 mold and the T3 modified Nafion measurements the two surfaces look vastly different. This observation is further confirmed by the area-scale results in Fig. 2, the relative area at the lower scales reveal the mold has a significantly larger area than was imparted on the Nafion. This indicates that only a partial transfer of the surface texture of the Nafion membrane occurred during the Nafion surface modification process explained in the methods. A possible explanation for the partial transfer could be because of the elastic deformation of the Nafion membrane. This deformation is recovered when the stress (force of the press during the hot pressing for surface modification) is removed.

Inherent Objective Characteristics

While measuring the molds with the Olympus LEXT3100 scanning laser confocal microscope, it became apparent using different objective lenses to measure the same object would likely yield different area-scale results. Some confocal measurement images (Fig. 3) obtained from the LEXT3100 had regions of large and small spikes on the surface which were not identified when using the optical white light setting. The optical white light setting is when the microscope uses light instead of a laser to display a real color image (2 dimensional only). Through further investigation this correlation was tested using measurements from the T3 mold. Measurements of the T3 mold were taken using the 20x objective lens and the 100x objective lens (Fig. 3). In theory the area-scale analysis of the same surface should be the same regardless of the magnification. Conducting an area-scale analysis on these measurements (Fig. 4) proved there is a significantly large difference in the relative areas using the different objective lenses. Therefore in order for a comparison of measurements from the Olympus LEXT3100 to be valid, both measurements must be taken while using the same objective lens. This observation was minded for all subsequent area-scale analyses.

Discrimination – Nafion

For preliminary testing, the modified Nafion membranes with the two extreme most cases were selected to be tested in the fuel cell. The two most extreme cases were determined to be membranes modified using molds G1 (lowest relative area) and T3 (highest relative area). Simply by observing the area scale-analysis (Fig. 5) of the two surfaces one cannot observe a clear differentiation of the two surfaces. However when a statistical F-test (Fig.6) is applied to both of the measurements, it is evident that the two measurements are able to be distinguished at or below the micrometer scale as indicated by the circle. From the area-scale plot (Fig.5) of the two measurements of the two membrane, there is about a 13% increase in relative area from the Nafion membrane modified by mold G1 to the Nafion membrane modified by mold T3 looking at the smallest scales. If the reaction which occurs in the fuel cell is affected by an increase in area then fuel cell performance is expected to see about a 13% increase.

Fuel Cell Tests

Fuel cell testing was completed in two trials. The first trial was with MEA 1_{smooth} and MEA 2_{rough}. The second trial was with MEA 3_{smooth} and MEA 4_{rough}. The surfaces referred to as smooth were modified using the G1 mold, which was subjected to grinding using 1 μm grit. The surfaces referred to as smooth were modified using the T3 mold, which was turned with a high feedrate.

The two trials differed in the preparation of the MEA. The first set of tests (MEA 1_{smooth} and MEA 2_{rough}) run on the fuel cell were run using MEAs prepared using the traditional procedure. The traditional procedure involved a hot pressing step, using a pressure of 2,000 lbs of force and 270°F of heat for the purpose of affixing the GDL to the catalyst. It was hypothesized that this step in the MEA preparation process could have eliminated the surface textures imparted on the Nafion membranes. The first two test results can be found in Fig. 7, under MEA 1_{smooth} (modified by mold G1) and MEA 2_{rough} (modified by mold T3). The same tests were carried out a second time using newly prepared MEAs, MEA 3_{smooth} and MEA 4_{rough}, which were prepared omitting the second hot pressing step. Instead of going to be hot pressed the membranes were removed of natural solvents in a 70°C oven for an hour. In this test MEA

3_{smooth} was modified by mold G1 and MEA 4_{rough} was modified by mold T3. The results for these two tests can also be found in Fig.7. The results from the second test show a slight improvement for the MEA modified by mold T3. These results are preliminary findings from this study. It is still unknown whether these results are statistically confirmed.

Membrane Electrode Assembly	Peak Current Density (mA/cm^2)	Peak Power Density (mW/cm^2)	Max. Relative Area	Peak Current Density Deltas (mA/cm^2)	Peak Power Deltas (mA/cm^2)	Max Scale for Discimination (μM)
MEA 1	917	250.4	1.14	MEA 2 - MEA 1=	MEA 2 - MEA 1=	10
MEA 2	976	242.8	1.33	59	-7.6	10
MEA 3	850	232	1.14	MEA 4 - MEA 3=	MEA 4 - MEA 3=	10
MEA 4	862	238.4	1.33	12	6.4	10

Table 4 - Fuel cell test result summary table.

Conclusions

1. Only a partial transfer of the mold surface texture to the Nafion membrane during the modification process.
2. When making measurements for comparison using the Olympus LEXT scanning laser confocal microscope, measurements must be taken using the same objective lens.
3. The modified Nafion membranes can be discriminated when using scales at or below one micrometer.
4. The fuel cell tests look good but are inconclusive due to not having been tested for repeatability.

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