공학석사학위논문

미세돌기 표면용 그리퍼를 위한 미세 핀 배열의 내구성 향상

Durability Improvement of Micro-Pin Array for a Gripper on Surface with Fine Asperities

2016년 2월

서울대학교 대학원

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지도교수 주 종 남

이 논문을 공학석사 학위논문으로 제출함

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기계항공공학부

윤 영 일

윤영일의 공학석사 학위논문을 인준함

2015년 12월

위 원 장 _____안 성 훈_________

부위원장 _____주 종 남_________

위 원 _____차 석 원_________

Abstract

In this study, durability of micro-pin array fabricated using nanosecond pulsed laser beam machining is improved for wall attachment mechanism of a climbing robot. Fabrication of micro-pin array using nanosecond pulsed laser beam machining was previously studied for simply clinging on the wall. However, due to low durability of pins, tips of pins were broken after multiple uses so the broken pins were not able to get interlocked. This study suggests a new method to increase durability of pin array for continuous use while increasing the maximum interlocking force of pins. Electrochemical etching process was used for durability improvement and interlocking force increment of pin array was gained through controlling line spacing and tip radius. Maximum interlocking force of pin has increased from 176.48 mN/mm^2 to 205.32 mN/mm^2, and 205.32 mN/mm^2 of constant and steady interlocking force could be achieved after multiple uses without damaging tip of micro-pin array.

Keyword : Micro-pin array, Laser beam machining, Electrochemical etching, Interlocking force, Durability, Gripper

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Chapter 1. Introduction

1.1. Study Background

A climbing robot has been one of the most popular but one of the most challenging topics of robotic research area recently. Depending on the surface roughness and geometry of the wall, different types of attachment methods were studied and applied on climbing robots [1-8]. These climbing robots are used for various purposes such as recon for military purposes or rescue missions. There are two main attachment types for climbing robots. First is adhesive that uses polymer for attachment method on smooth surface such as glass. Adhesive [6-8] uses van der Walls force for attachment and directional adhesion method for detachment [8]. Stickybot is the most popular example of it [1]. Second is spine attachment method that targets for rough surface such as brick or concrete. Spine mechanism simply cling hook shaped spine on bumps of the wall. Spinybot is the most popular example of it [2].

Attachment method using micro-pin array, which was previously studied, targets for surface with roughness smaller than that of Spinybot [9]. Shown in Fig. 1.11 is the laser beam machining setup for fabricating micro-pin array. Ytterbium fiber laser with 1064 nm wavelength is used for fabrication. This process utilizes recast layer that is piled up during fabrication to form pin shape. Detailed fabrication process is explained in chapter 2.

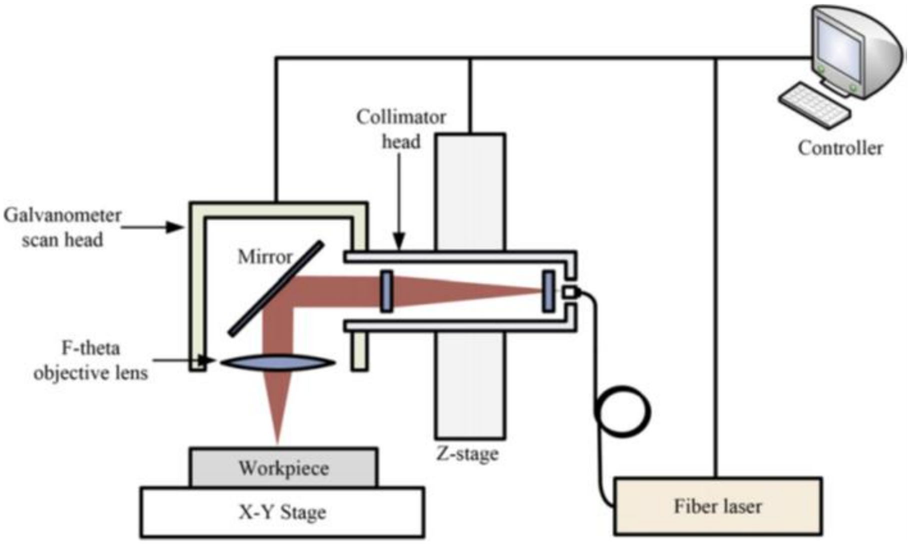


Figure 1.11. Laser beam machining setup for fabrication of micro-pin array [9]

General spine mechanism uses hook shaped spine to cling its weight on the bump of the wall. Unlike spine mechanism, micro-pin array consist of hundreds of straight pins which are interlocked on asperities of the wall [9]. As shown in Fig. 1.12, hundreds of pins are formed and are interlocked on asperities of surface.

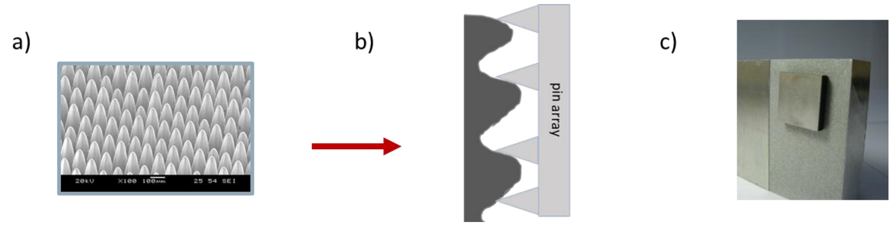


Figure 1.12. General image of micro pin array and application: a) Image of micro-pin array, b) Attachment method, c) Application on climbing mechanism [9]

Each attachment method studied aims for surface with different surface roughness. As chart shows in Fig. 1.13, Stickybot targets for soft surface with surface roughness less than 1 μm while Spinybot targets for rough surface with surface roughness over 100 μm. Micro-pin array is a mechanism that aims for surface with surface roughness in between.

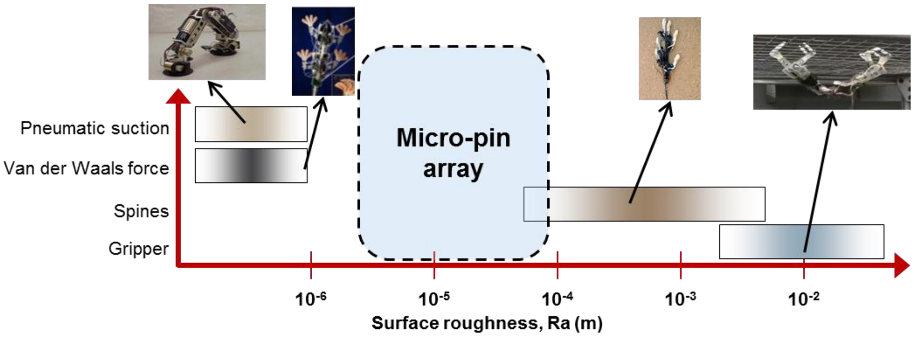


Figure 1.13. Target surface of micro-pin array [9]

1.2. Purpose of Research

Micro-pin array has two weak points that holds back from applying on climbing robot mechanism. Mainly, durability of micro-pin array is very low that reuse or multiple uses is impossible. Multiple uses of micro-pin array leads to larger tip radius that pins cannot get interlocked on asperities of wall as before because tip of pin breaks. This is due to weak tip of pin that compose of recast layers gained from laser beam machining process. Shown in Fig. 1.21 is the actual feature of micro-pin array after multiple uses. Additionally, interlocking force that micro-pin array can produce is small that it is hard to endure weight of mechanism. In order to apply micro-pin array in actual climbing mechanism, both issued problems need to be solved. In this study, and electrochemical etching process are suggested to solve the durability issue, and controlling line spacing and tip radius is suggest for increment of interlocking force so that micro-pin array can be actually applied on mechanism such as climbing robots.

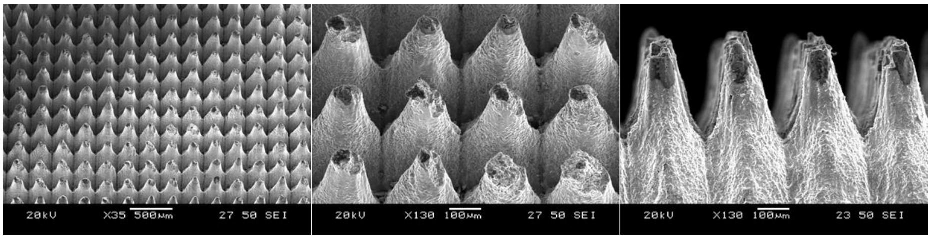


Figure 1.21. Tip (recast layer) break after multiple use

In section 2, method of fabricating micro-pin array, electrochemical etching, and setting up interlocking force measurement system are explained. In section 3, results of fabrication of micro-pin array before and after etching are displayed along with interlocking force results. In section 4, Discussions on results of this study are displayed along with gripper feasibility test. Lastly in section 5, conclusion with future work is presented.

Chapter 2. Methods

2.1. Fabrication of micro-pin array

Ytterbium fiber laser with 1064 nm wavelength is used as laser source for this study. Laser is installed on 3-axis stage. X-Y stage is controlled to set the fabricating position and Z stage is controlled to set the focal point of the laser on the surface of workpiece as explained in Fig. 1.11. Micro-pin array is fabricated on 5 X 5 mm^2 Stainless Steel 304 of 1 mm thickness.

Shown in Fig. 2.11 is the laser path for fabrication of micro-pin array. As laser passes by the path that was designed, recast layer starts piling up on a zone called, ‘Pitch’. As shown in Fig. 2.11 b), recast layer will keep piling up eventually making arrays of pin features. Power of laser and number of scanning are main control parameters that can vary tip radius of pin which are crucial factors in deciding interlocking force. It was studied that pin with smaller tip radius has produced higher interlocking force [9]. High power will produce blunt tip because great amount of recast layer will pile up due to high energy while low power will produce sharp tip due to small amount of recast layer pile up. Increment of number of scanning leads to increment of heat applied on boundary of pin that will also affect radius of tip of pin. Combination and variation of these two parameters can produce sharp tip in short machining time.

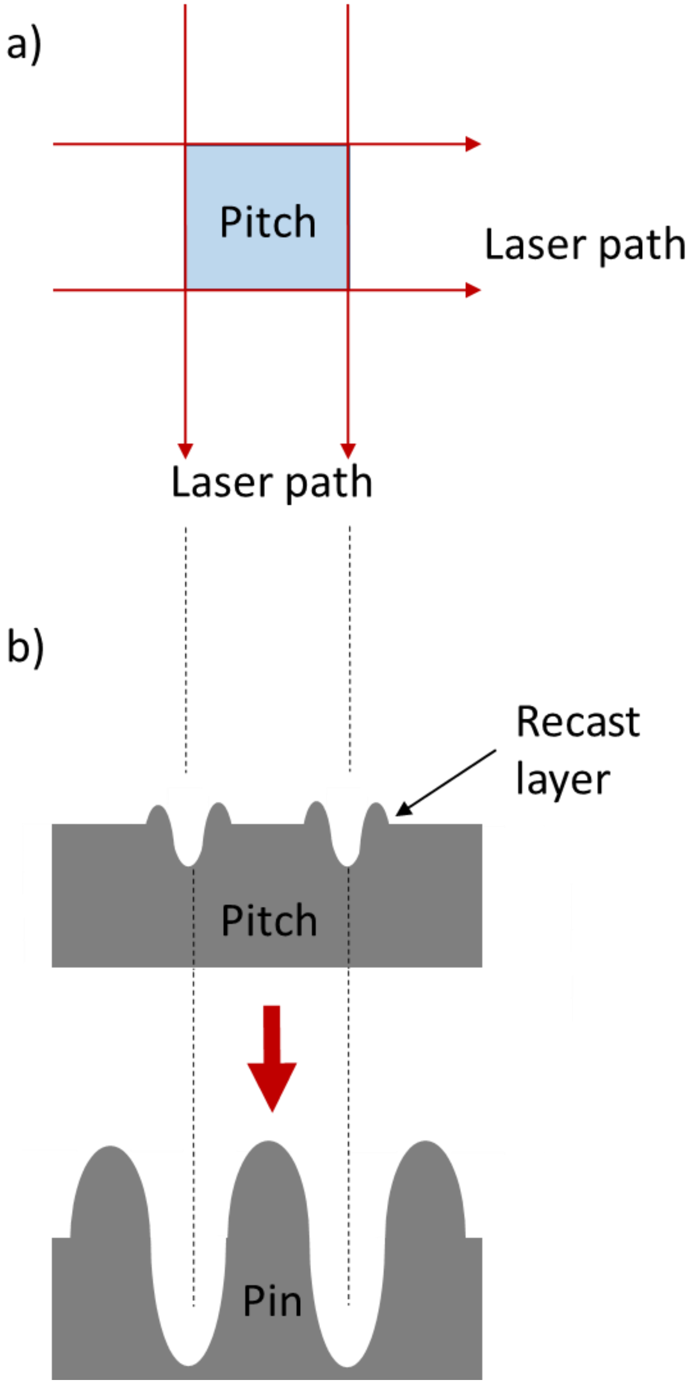


Figure 2.11. Process of recast layer piling

2.2. Electrochemical etching

Electrochemical etching is generally used for removing unwanted burr that occurs from fabricating process in order to gain clean and high quality surface of a product [10][11]. Electrochemical etching is non-contacting process that removes recast layer and heat affected zone gained from laser beam machining process. Etching process is generally isotropic and is more focused on tips or peaks of a fabricated product due to high current density [10].

One of the main purposes of this study is to improve the durability of micro-pin array for actual application on climbing robots. In order to prevent tip break for reuse, recast layer need to be removed. Recast layer gained from machining process contain oxygen which makes it brittle due to oxygen interruptions in original stainless steel. Electrochemical etching is a method for removing oxygen gained from machining process of micro-pin array. This is because electrochemical etching is capable of removing oxygen while keeping conical shape of pin and is a non-contacting and simple process. Machining time and quality of machined product are the most crucial factors in fabrication, and electrochemical etching is a popular method for producing high quality surface in short time process.

Shown in Fig. 2.21 is electrochemical etching experimental setup. Micro-pin array is attached to positive side and STS 304 plate is attached to negative side. Sulfuric acid of 1 mole is used as electrolyte which is commonly used to etch stainless steel products [10]. Voltage and etching time are main control parameters that decide etching level.

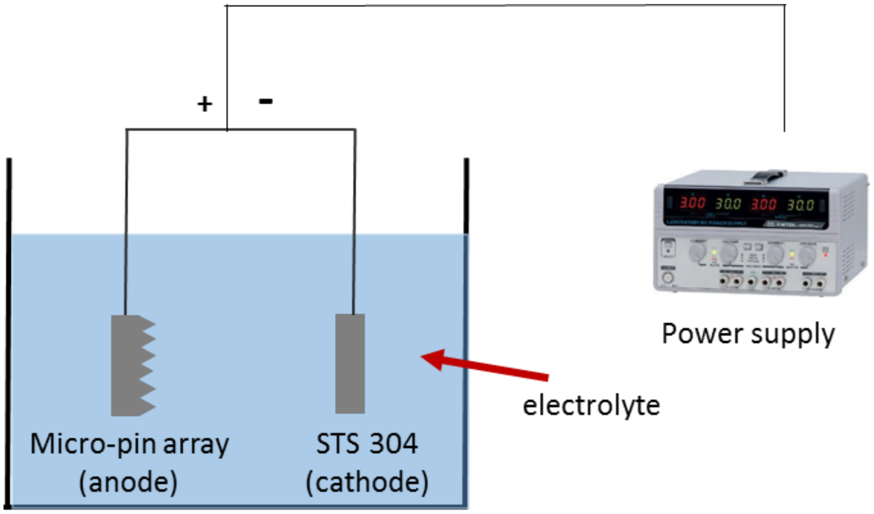


Figure 2.21. Electrochemical etching experimental setup

Micro-pin array has conical shape as shown in Fig. 2.22. Shown in arrows is the direction of etching. Tip is etched faster due to high current density thus keeping pin shape after etching process. Piled up area, especially tip, is etched first because current is focused on smaller area as peak has smaller area than plane surface. And the section with bigger area are etched next [10]. This is why pin could maintain original geometry after etching process. Through etching, recast layer shown in Fig. 2.22 are removed thus gaining final pin.

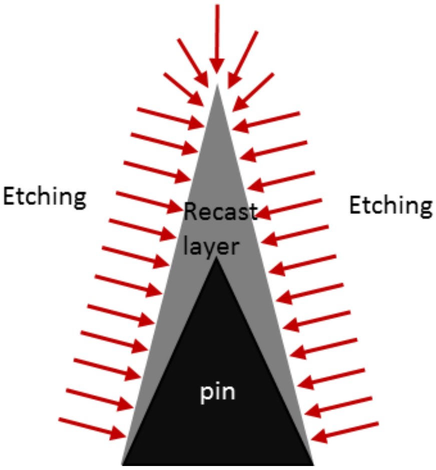


Figure 2.22. Etching process

Shape of pin after etching is analyzed through Scanning Electron Microscope (SEM) and composition of oxygen after etching is analyzed through Energy Dispersive Spectroscopy (EDS). Gaining small tip radius is crucial because with small tip radius, pin array can have enough space for interlocking on wall. Additionally, pins with small tip radius can interlock with surface with small surface roughness thus increasing application range.

2.3. Interlocking force measurement system

Improved micro-pin array for actual application are fabricated and experimental setup for force measurement was constructed in order to confirm the improvement of durability and interlocking force. Shown in Fig. 2.31 is overall process of measuring interlocking force. From load cell setup, current is measured and is amplified through amplifier. Through DAQ, data is transferred to PC to be displayed.

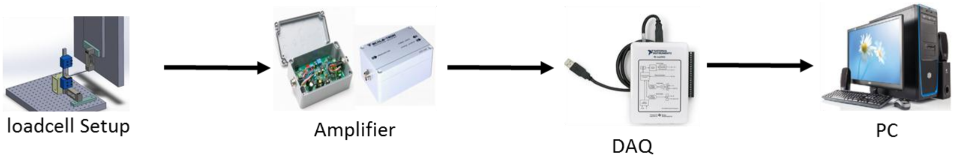
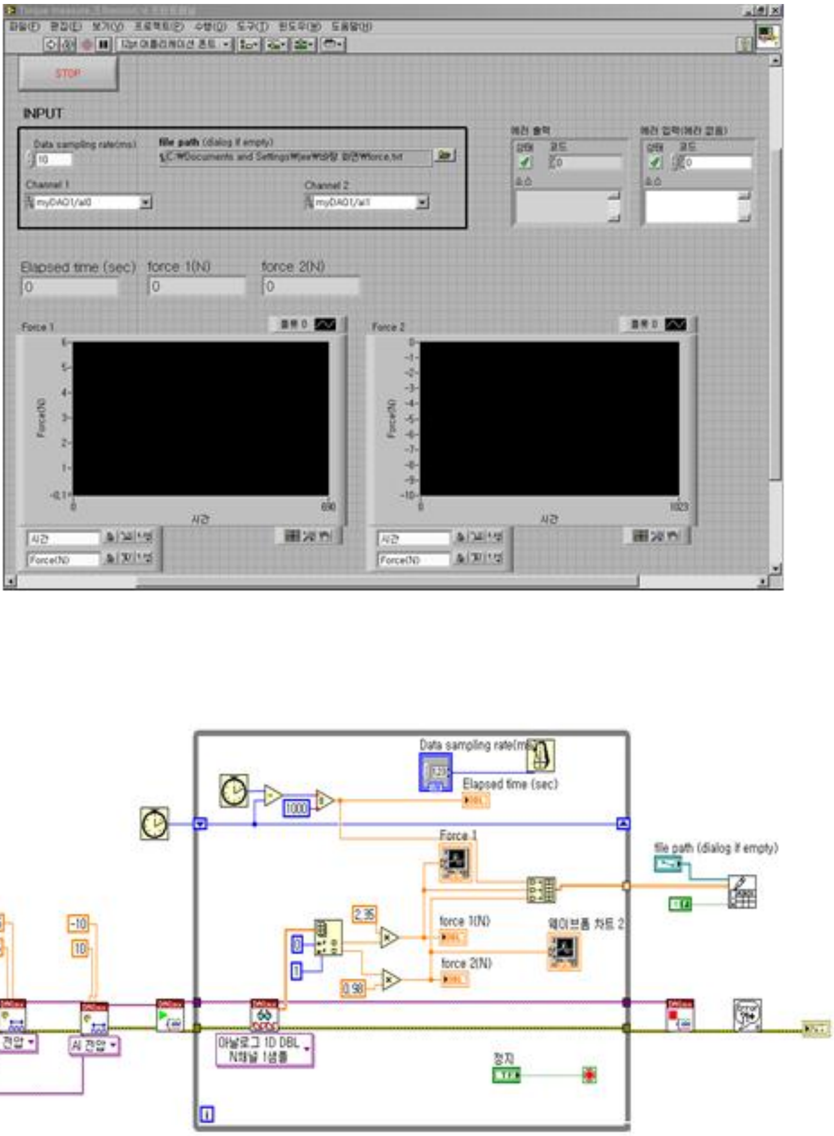


Figure 2.31. Overall diagram of data acquisition process

Labview was used for convenient data acquisition process. By building Labview program as shown in Fig. 2.32, an acquisition of real-time interlocking force was possible.



Data sampling rate(ms) 10

Channel 1 myDAQ1/ai0

Channel 2 myDAQ1/ai1

Elapsed time (sec) 0

force 1(N) 0

force 2(N) 0

Figure 2.32. Normal force and interlocking force measurement panel and Labview block diagram

The main purpose of load cell setup on 3-axis stage was to minimize possible error in measuring both interlocking force and normal tapping force. Two load cells (capacity 600 g, resolution 0.02 %, Ktoyo) are installed to measure force as shown in Fig. 2.33. Vertical slider and two parallel blocks are installed in order to apply exact and even normal force for experiment.

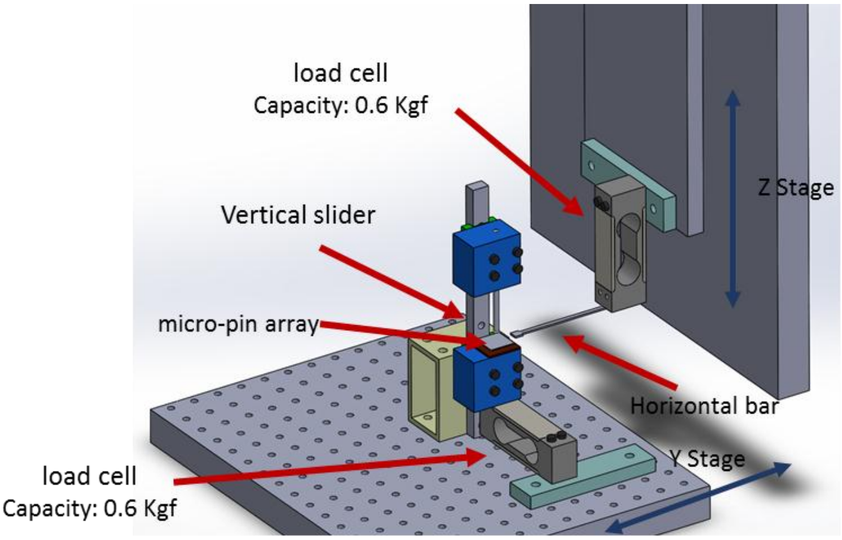


Figure 2.33. Interlocking force measurement system

Small angle error among the components of the system could lead to inaccuracy in interlocking force measurement. Due to small size of micro-pin array, it is hard to apply exact horizontal force when pin array is not parallel to the top load cell. Horizontal bar was installed on top load cell in order to push micro-pin array in exact horizontal direction. On the top surface of bottom block, target surface is positioned and micro-pin array is laid on target surface as shown in Fig. 2.34.

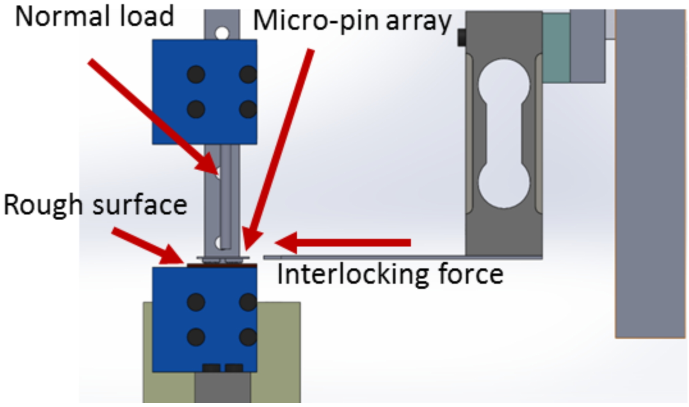


Figure 2.34. Parallel force measurement

In this study, interlocking force was measured on fabricated tungsten surface. Fabricated tungsten surface is used for testing because it could produce surface with surface roughness close to real target surface and it could endure pin testing without breaking. Tungsten surface was also fabricated using laser beam machining explained in chapter 1.

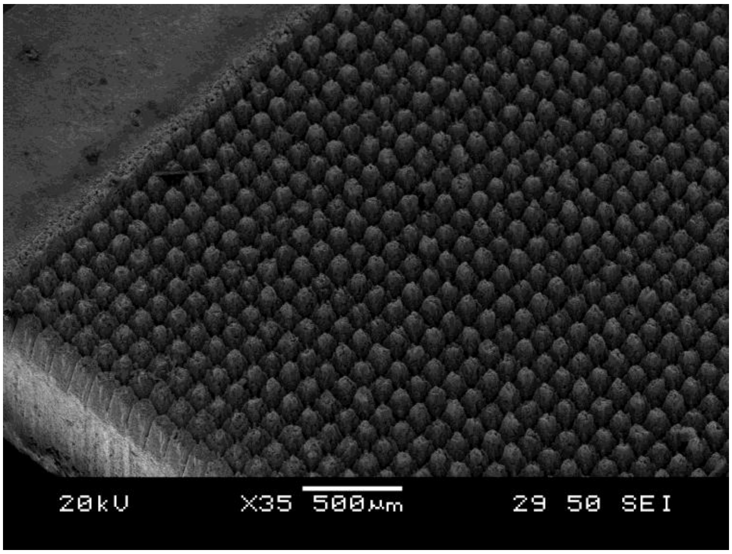


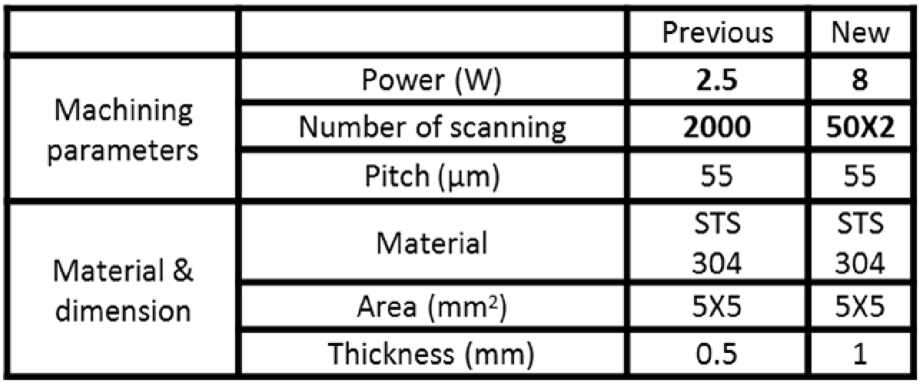
Figure 2.35. Fabricated tungsten surface for interlocking force test

Fabricated tungsten surface had surface roughness of 7 μm which is in a range of target surface of micro-pin array. Machining parameters of 15 watts and 1000 times were used.

Chapter 3. Results

3.1. Fabrication of micro-pin array

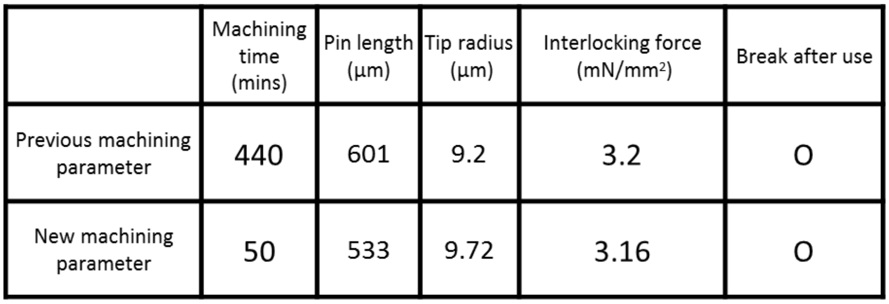
With machining parameters of previous micro-pin array as shown in Table 3.11, it took 440 minutes to fabricate micro-pin array [9]. After multiple parameter tests, new machining parameter was found that could keep the shape of micro-pin array with previous machining parameter. Fabrication with new machining parameters only took 50 minutes.



		Previous	New
Machining parameters	Power (W)	**2.5**	**8**
	Number of scanning	**2000**	**50X2**
	Pitch (µm)	55	55
Material & dimension	Material	STS 304	STS 304
	Area (mm^2)	5X5	5X5
	Thickness (mm)	0.5	1

Table 3.11. Previous machining parameters vs. new machining parameters

Various measurements were taken for micro-pin arrays with previous machining parameter and new machining parameter for comparison. While machining time has decreased greatly, pin length was only 68 µm apart from previous study and tip radius was kept almost same. As interlocking force with both machining parameters were measured, both showed similar results. Thus, new machining parameter was selected for this study.



	Machining time (mins)	Pin length (μm)	Tip radius (μm)	Interlocking force (mN/mm^2)	Break after use
Previous machining parameter	440	601	9.2	3.2	O
New machining parameter	50	533	9.72	3.16	O

Table 3.12. Comparison between previous and new micro-pin array

For micro-pin array with previous design, line spacing was 5 of 10 μm making total of 50 μm between every micro-pin as shown in Fig. 3.11. Laser path is 10 μm apart and only 5 lines of paths were drawn between pins. This has produced micro-pin array shown on the left of Fig. 3.11. After multiple testing, it was clear that gap between each tip of micro-pin was too small for asperities of target surface with over 100 μm gap. Thus we tried to vary the spacing between each pin in order to find the best line spacing for interlocking on asperities of the surface that we are targeting for.

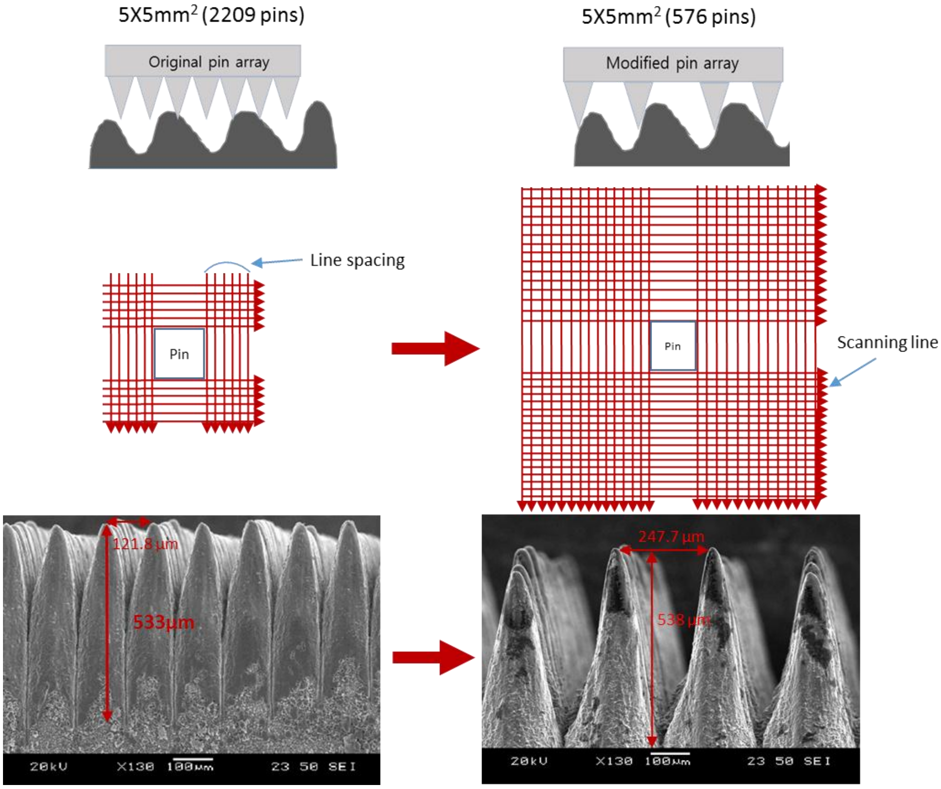


Figure 3.11. Original and modified pin array

Interlocking force of micro-pin array with various line spacing was tested to find the best line spacing for target surface as shown in Fig. 3.11. Previous spacing was named ‘single spaced’ and multiplied spacing were named ‘double, triple, and quadruple.’ Interlocking force test result has shown that triple spaced micro-pin array produced largest interlocking force. As we increased line spacing, force has increased and then dropped after triple spacing. Thus triple spaced design was chosen as final. In this study, testing surface was tungsten surface with 7 µm of surface roughness. Triple spacing was best fit for such target surface and when roughness changes, best fit spacing will change accordingly.

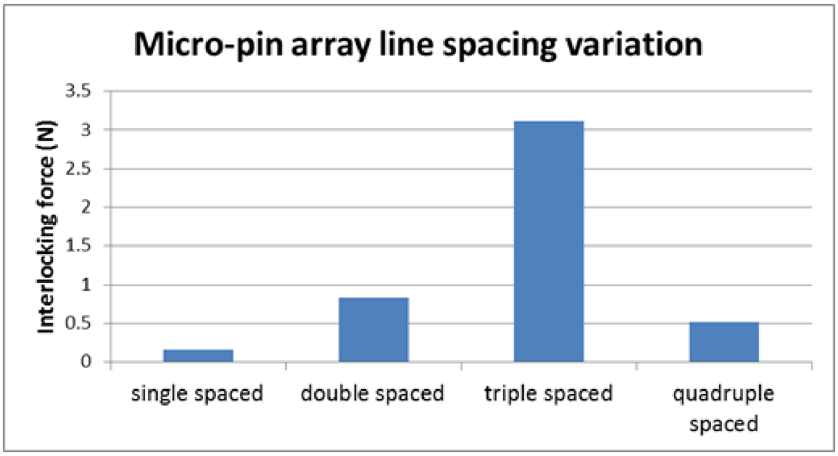
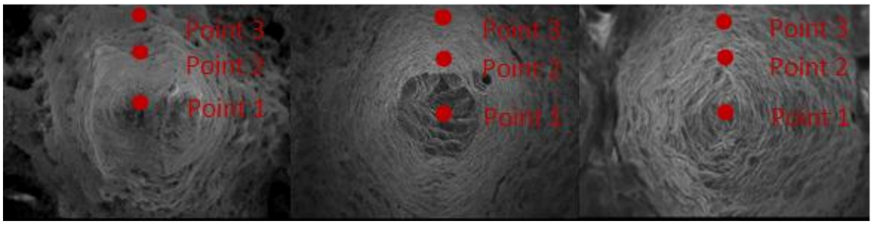


Figure 3.12. Interlocking force for various line spacing

3.2. Electrochemical etching and Energy Dispersive Spectroscopy

As final machining parameters of micro-pin array in this study were decided, electrochemical etching was done on micro-pin array in order to remove recast layer containing oxygen that makes micro-pin array brittle. In order to check the trend of etching result depending on voltage, three different parameters were tested as shown in Fig. 3.21.

Energy Dispersive Spectroscopy is used to measure composition of oxygen on the surface of micro pin array. Three points were tested; the peak, middle, and bottom point.



a) 7V 120sec b) 9V 120sec c) 11V 120sec

Figure 3.21. Top view of micro-pin array with various etching voltages

Out of three points that are tested, main concern was on the first point, which is the broken point of non-etched micro-pin array. It was clear that 7 V etched condition has shown great composition of oxygen while 11 V etched condition has shown minimal composition of oxygen. It was evident that etching was removing more oxygen layer as parameters increased from 7 V to 11 V.

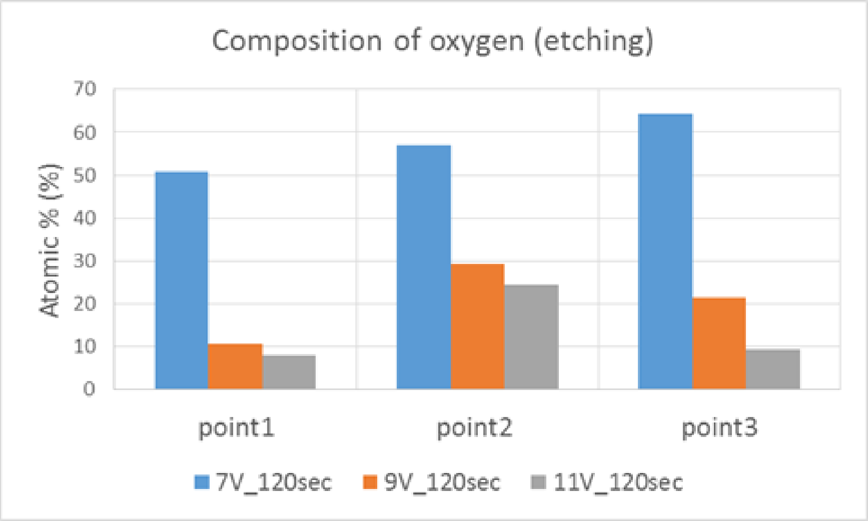
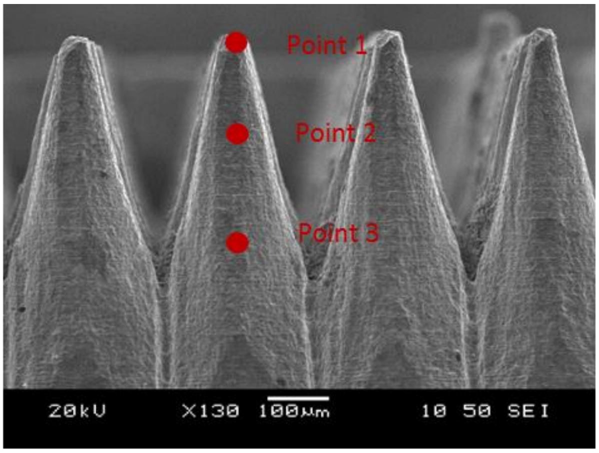


Figure 3.22. Composition of oxygen after etching process

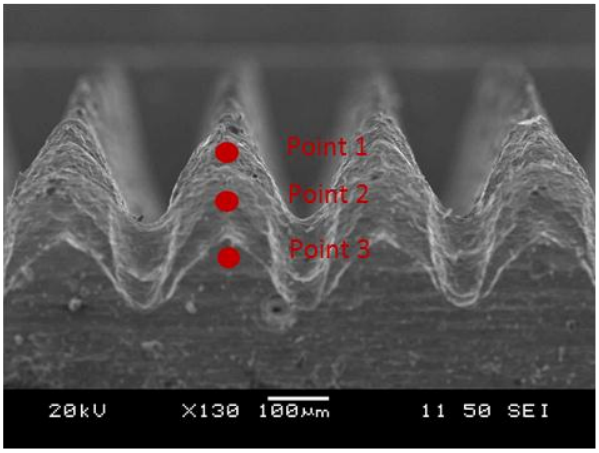
As effect of etching was confirmed and first parameter test was done, we narrowed down to two different etching conditions to find final etching condition. First condition was 5 V and 120 seconds of etching and second was 10.5 V and 240 seconds. For 5 V and 120 seconds etching condition, pin showed similar geometry with sharp edge while containing too much oxygen on the tip as Table 3.21 shows. For 10.5 V and 240 seconds etching condition, oxygen composition was under 10 percent for tip while the shape of pin was demolished and could not keep sharp tip.

a)



	Point 1	Point 2	Point 3
	Atomic %	Atomic %	Atomic %
Oxygen	**23.04**	**37.27**	**46.91**

b)

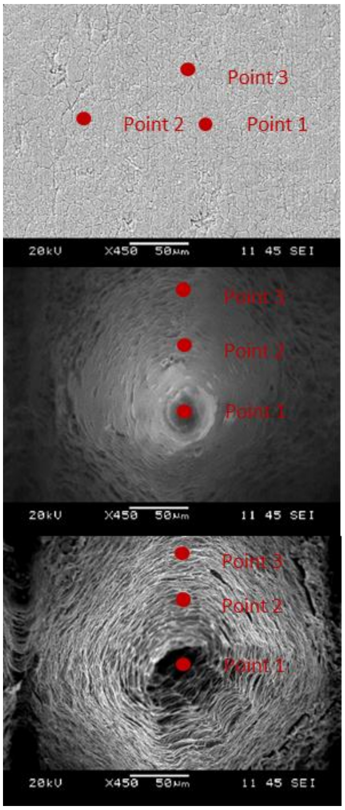


	Point 1	Point 2	Point 3
	Atomic %	Atomic %	Atomic %
Oxygen	**7.77**	**2.47**	**7.33**

Figure 3.23. Oxygen composition of a) 5 V 120 sec etching, b) 10.5 V 240 sec etching

Final etching condition was decided based on two different etching condition cases of 5 V with 120 seconds and 10.5 V with 240 seconds. Shown in Table 3.31 are the oxygen compositions of Stainless steel 304 plate, micro-pin array without etching, micro-pin array with final etching condition in order.

It is clear that a normal stainless steel plate contain very little oxygen on the surface while micro-pin array gained great amount of oxygen on the surface. By etching with right condition, oxygen composition was decreased down to about 7 percent.



STS 304 surface

	Point 1	Point 2	Point 3
	Atomic %	Atomic %	Atomic %
Oxygen	**3.46**	**0.67**	**0**

Micro-pin array

	Point 1	Point 2	Point 3
	Atomic %	Atomic %	Atomic %
Oxygen	**53.23**	**47.94**	**38.82**

10.5V 120sec etched pin array

	Point 1	Point 2	Point 3
	Atomic %	Atomic %	Atomic %
Oxygen	**6.92**	**16.91**	**20.19**

Figure 3.24. Final etching results with EDS

As composition of oxygen was decreased down to 7 percent, the shape of the pin was observed. When comparing the pin before and after etching with final etching condition, geometry of pin was kept similar. Tip of micro-pin array got even smaller after etching from 19.44 µm to 9.74 µm. Small diameter of tip can lead to better interlocking on smaller asperities of wall. Moreover, it leads to increment of interlocking force when interlocked on asperities of wall.

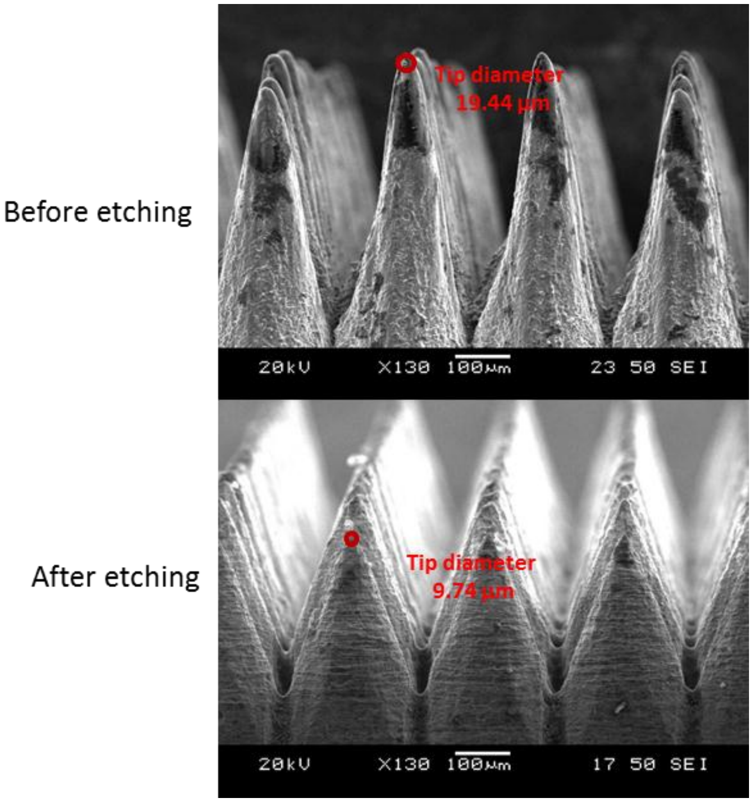


Figure 3.25. Tip radius before and after etching process

3.3. Interlocking force test

Micro-pin arrays with four final etching conditions were used for interlocking force measurement. First graph of Fig. 3.41 is micro-pin array without etching and rest graphs are micro-pin array with various etching conditions. The last one is pin array with final etching condition.

For micro-pin array without etching, it is evident that interlocking force has decreased greatly as trial was continued. For pin array with etching condition of 5 V and 120 seconds, interlocking force has decreased while not as drastically as pin array without etching. As we tested micro-pin array with etching condition of 10.5 V and 240 seconds, interlocking force was quite steady throughout multiple force testing however not producing high interlocking force. Micro-pin array with final etching condition of 10.5 V and 120 seconds has shown high interlocking force that was steady throughout multiple trials. By comparing multiple interlocking force trial results, it was evident that the last etching condition has produced strong and steady interlocking force.

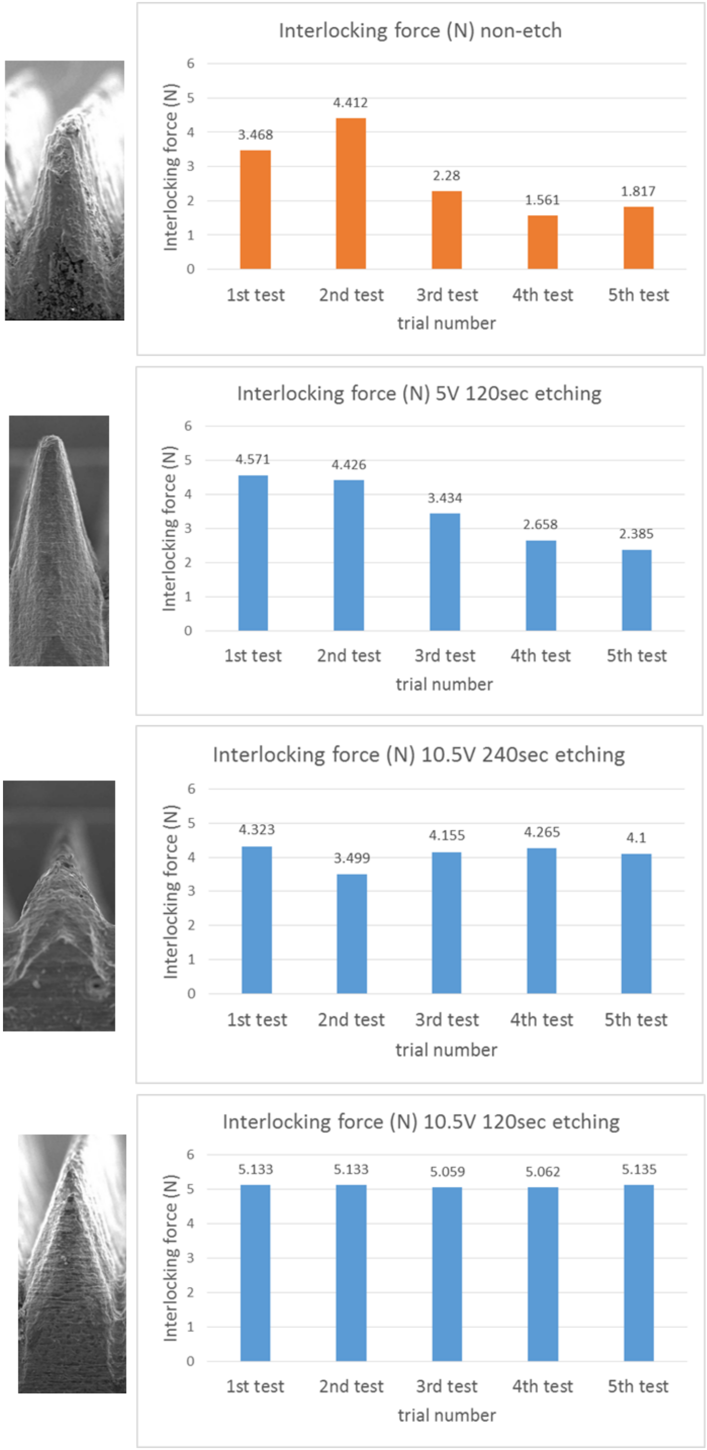


Figure 3.31. Interlocking force of micro-pin array with various etching parameter

Chapter 4. Discussions

4.1. Analysis on tip break of micro-pin array

As interlocking force of micro-pin array varied according to different electrochemical etching parameters, reasons for variation of interlocking force and tip radius of pin were analyzed. Variation of interlocking force and tip radius during multiple force tests have shown etching process has crucial impact on durability of micro-pin array. It was clear that recast layer that compose of oxidation layers are brittle and is the weakest point of micro-pin array for application.

Before force test, both non-etched pins and pins with final etching parameter have shown sharp tip. However, as Fig. 4.11 shows, shape of pins varied greatly after multiple interlocking force tests and micro-pin array without etching had all the pins tips broken.

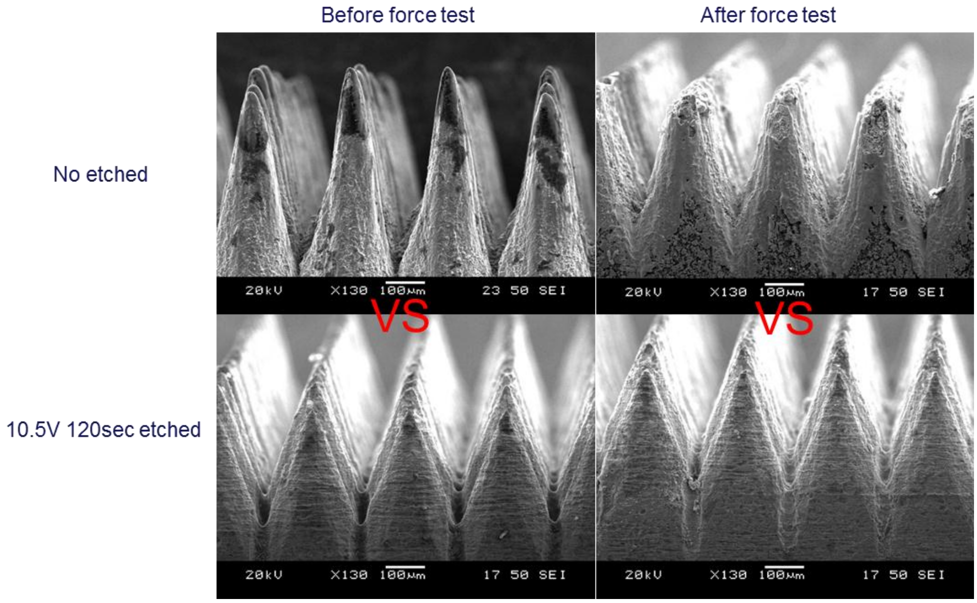


Figure 4.11. Tip of micro-pin array after force test (non-etch vs. etch)

The average of tips of micro-pin arrays after force test was measured. Pin array with final etching condition kept very small tip radius even after multiple force test. However, pin array without etching produced very large tip radius. It was concluded that etching was very effective in keeping the small tip radius of micro-pin array which directly leads to durability of micro-pin array for real application.

	pin tip after force test	**average**
10.5V 120sec etched	(tip radius) µm	**7.525**
No etched	(tip length) µm	**50.325**

Table 4.11. Tip measurement after force test (non-etch vs. etch)

Additionally, maximum interlocking force of micro-pin array was improved. Maximum interlocking force of pin was improved from 176.48 mN/mm^2 to 205.32 mN/mm^2 through electrochemical etching. It was very clear that as trial went on, force difference between etched pin and normal pin got more critical due to tip break of normal pin.

4.2. Feasibility of micro-pin array on gripper

Recently, there have been few studies on gripping mechanism for application on the climbing robots [12-15]. As micro-pin array with high durability was obtained in this study, feasibility of the new gripper with improved micro-pin array was tested. The gripper was tested on sandpaper which is closer to real surface than fabricated tungsten surface. The surface roughness of sandpaper was around 8 μm which is target surface for micro-pin array of climbing robot.

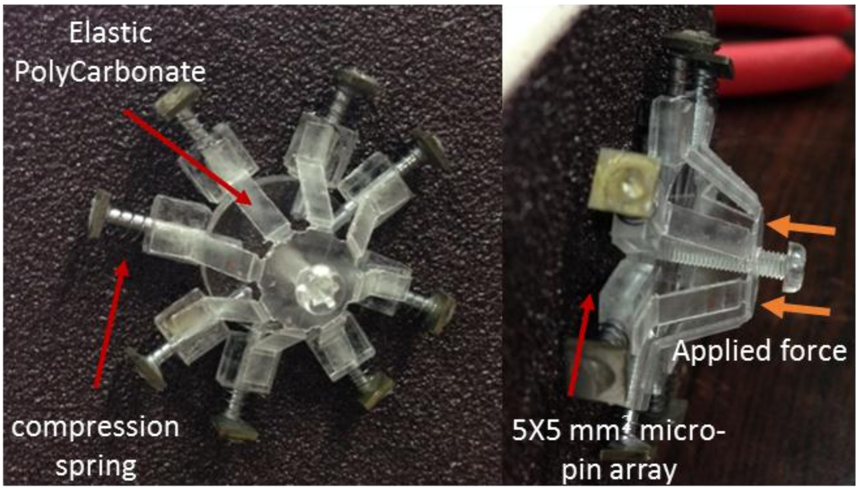


Figure 4.21. The gripper with improved micro-pin array.

Weight (g)	8.02
Material	Acryl, Polycarbonate, Aluminum
Dimension (mm³)	60 X 60 X 50
Maximum loading (g)	10

Table 4.21. Specifications of the gripper

Eight sets of 5 X 5 mm^2 micro-pin array pads are installed on the feet of the gripper. Eight compression springs were also installed to keep micro-pin array in hold. Acryl and aluminum bar were used for the main body of gripper. Top part that pushes micro-pin array outward was manufactured using elastic polycarbonate for flexible bending motion. It was suitable for applying normal tapping force without breaking the gripper. Total weight of the single gripper was around 8 g including micro-pin array pads. Shown in Fig. 4.21 is actual image of the single gripper. Shown in Table 4.21 is the specification of gripping mechanism. Most of the parts were acryl to reduce weight.

The gripper is actuated in two step process. First, we push the elastic polycarbonate cover shown in arrow which will push 8 blocks with micro-pin array pads attached on the bottom to outward direction against spring force as shown in Fig. 4.22. As we apply tapping normal force on the block with micro-pin array, micro-pin array pads will get interlocked with the asperities of sandpaper surface. As releasing polycarbonate part, spring force will push each block toward center causing gripping force to hold the gripper on the surface.

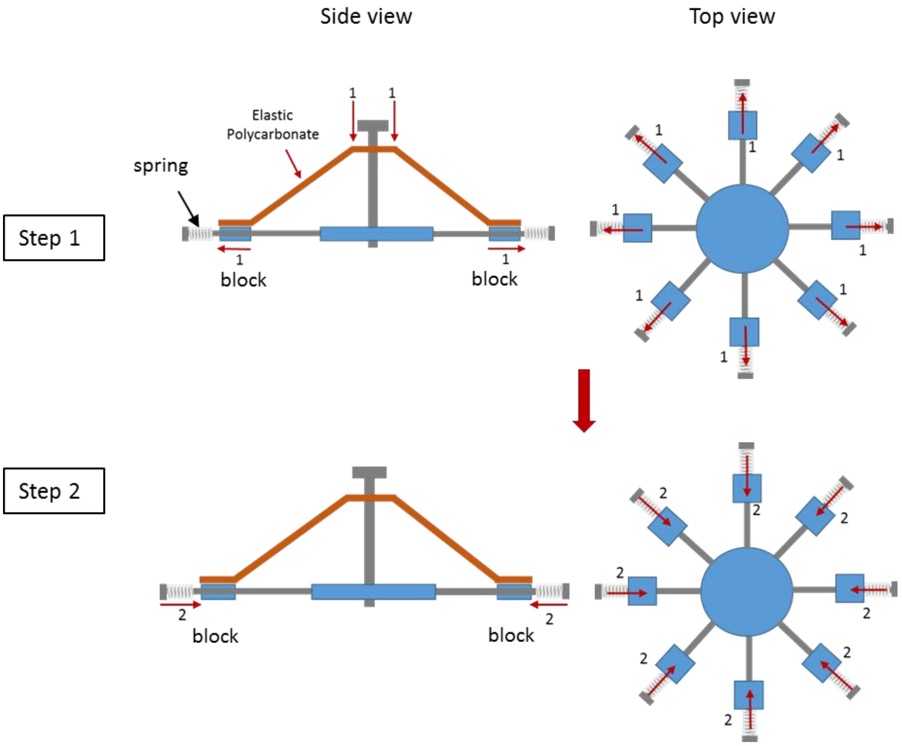


Figure 4.22. Gripping motion of gripper

Chapter 5. Conclusions

5.1. Conclusions

In this study, two main issues of micro-pin array for application are comprehended and solutions are provided with new machining parameters and electrochemical etching process.

Main issue of micro-pin array, durability, was solved through electrochemical etching process. Durability of micro-pin array was low due to recast layer that is piled up during laser beam machining. Through electrochemical etching process, recast layer that compose of oxidation layer was removed. Oxidation layer is very brittle, which is the main reason for tip break of micro-pin array when interlocking on asperities of wall. Through electrochemical etching, high durability was achieved thus repeated use was possible for real application.

Along with durability, interlocking force of micro-pin array also has improved. New machining parameter and line spacing were found through multiple parameter tests. 8 watts and 100 times of machining parameter with tripled line spacing was selected as final for fabricating micro-pin array. With new machining parameters, fabrication time was decreased greatly and through etching, and controlling line space, increment of interlocking force could be gained. Due to increment of interlocking force, more weight of robot can be added on the micro-pin array to hold. Increment of maximum weight pin array can hold is crucial because weight reduction of robot body is very troublesome.

As durable micro-pin array was gained, feasibility testing was done by attaching micro-pin array pad to a gripper. The Gripper was applied on sand paper which is closer to the real surface than fabricated tungsten surface.

Through improvement of micro-pin array and feasibility testing of gripper with micro-pin array, validity was confirmed but few more works are needed in order to have a complete climbing robot with micro-pin array mechanism; new mechanism that can apply hard tapping normal force on micro-pin array is required addition to the gripper. With new mechanism added, complete robot with multi-directional movement will be possible.

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국문초록

본 연구에서는 레이저 가공법을 통하여 가공된 미세 핀 배열의 내구성 향상 연구를 통해 실제 벽면 등반 로봇에 적용이 가능하도록 하였다. 벽면 접착을 목표로 하는 미세 핀 배열의 레이저 가공법은 기존에 연구되었지만, 핀의 약한 내구성 때문에 여러 번 사용 후 핀은 부러지게 되었으며, 그로 인하여 벽에 다시 부착할 수 없었다. 본 연구는 그러한 미세 핀 배열의 내구성을 증가시키며 동시에 최대의 인터라킹(interlocking) 힘을 증가시킬 수 있는 방법을 제안한다. 이 연구를 통해서 새로운 최적의 가공 조건인 8 와트의 출력과 100번의 조사횟수를 얻게 되었고, 10.5 볼트와 120 초라는 전해 에칭 조건을 통하여 견고성 향상과 최대 인터라킹 힘의 증가를 이룰 수 있었다. 에칭 과정을 통하여 최대 인터라킹 힘은 176.48 mN/mm^{2}에서 205.32 mN/mm^2 으로 증가하게 되었으며, 여러 번의 실험 후에도 지속적인 205.32 mN/mm^2 의 힘을 얻을 수 있었다.

키워드: 미세 핀 배열, 레이저 가공법, 전해 에칭, 인터라킹 힘, 내구성, 그리퍼

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