Optimization of Electro Chemical Machining of ASTM 52100 Bearing Steel (100 Cr6) for Machining Time, Surface Roughness and Kerf Angle

Research Student

Muhammad Saad Fasih

MS (Design & Manufacturing Engineering)

NUST201463092MSMME62014F

Supervisor: **Dr. Syed Hussain Imran Jaffery**

Department of Design and Manufacturing Engineering (DME)

School of Mechanical & Manufacturing Engineering (SMME)

National University of Science & Technology (NUST)

Islamabad, Pakistan.

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Author

Muhammad Saad Fasih

Regn Number

NUST201463092MSMME62014F

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Thesis Supervisor:

Dr. Syed Hussain Imran Jaffery

Thesis Supervisor's Signature: _____

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SCHOOL OF MECHANICAL & MANUFACTURING ENGINEERING

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AUGUST, 2018

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Muhammad Saad Fasih

Registration Number
NUST201463092MSMME62014F

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Dr. Syed Hussain Imran Jaffery

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Guidance and Examination Committee

Name: Dr. Liaqat Ali Signature: _____

Name: Dr. Mushtaq Khan Signature: _____

Name: Dr. Emad Ud Din Signature: _____

Advisor's Name: Dr. Syed Hussain Imran Jaffery Signature: _____

Dated: _____

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Head of Department Dated Dean/Principal Dated

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Abstract

Various types of Steel alloys are available in market, each of whose utilization varies with amount of different elements it contains. ASTM 52100 Steel or 100Cr6 Bearing is a specific type of steel alloy (with high carbon contents along with chromium contents) which has been hardened. It is mainly used in the fabrication of different bearings because of its higher wear resistance and good fatigue life. Grooves are fabricated on bearings for the purpose of self-pumping of lubricant to reduce friction and increase wear life of bearings. In this thesis, electro-chemical machining method of fabrication of grooves on bearings is worked upon. In electro-chemical machining, the work piece which is often rendered anode is placed in a bath of electrolyte solution along with the cathode and DC current is supplied through variable power supply. Electro chemical reaction takes place in the bath and metal from the work piece is dissolved in the solution. In this thesis work, grooves with micro depth are fabricated on samples of 100Cr6 Bearing steel and the factors on which electro chemical machining depends (electrolyte concentration, current, temperature of solution) are varied to get responses in terms of time required to machine 10 micron depth, surface roughness of etched area and kerf angle of the groove machined. These responses are optimized subsequently.

Keywords: *Electro chemical machining, Surface Roughness, Kerf Angle, Bearing Steel*

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CHAPTER 1: INTRODUCTION

ASTM 52100 Bearing steel or 100Cr6 Bearing steel:

ASTM 52100 Bearing steel or 100Cr6 Bearing steel is a high carbon content steel with chromium contents which has been hardened. It is a low alloy steel. Chemical composition of 100Cr6 Bearing steel is given in the table below:

Table 1.1: Composition ASTM 52100 Bearing steel

Element	Car	Silicon	Mn	Phosphorus	Chromium	Mo	Sulfur
% Comp	0.95-1.1	0.15-0.35	0.25-0.45	0.03 max	1.35-1.65	0.1 max	0.2 max

Corrosion resistance of 100Cr6 Bearing steel is not very good because of lower chromium contents. It is particularly used in manufacturing of high precision miniature bearings as it has higher wear resistance and good fatigue life. Some of the advantages of 100Cr6 Bearing steel are listed below:

1. It is used in the production of roller bearings and ball bearings
2. It has long working life
3. It is very cost efficient
4. It can continuously operate at higher temperature touching 120 °C
5. It has good hardness values at room temperature

The major applications of 100Cr6 Bearing steel are in the field of bearing manufacturing. The components which come under regular and high stresses like aircraft bearings are manufactured from 100Cr6 Bearing steel.

Grooves Fabrication on Bearings:

Spiral or logarithmic slits or grooves are fabricated on bearings through different methods. The purpose of this this grooving is to reduce friction and wear. Due to the presence of these grooves on bearings, self-pressurization occurs and there is no need for external pressurization of lubricants.

Bearings with spiral grooves on them are also called self-acting bearings or contact less bearings as they build their own pressure to separate the two bearing surfaces.

Fabrication Methods of Grooves:

Following are some common methods for the fabrication of grooves on bearings:

1. Etching
2. Mechanical Grooving
3. Laser Etching
4. Soldering

Etching:

This is probably the easiest and most common method to fabricate grooves on the bearing surfaces. In this process work piece is made anode while it is dipped in a bath containing chemical etchant and cathode. Direct current is applied to the cathode and anode via variable power supply and etching impressions are made. The factors on which electro chemical etching depends are:

1. Etching time
2. Electrolyte concentration
3. Temperature of solution
4. Circulation of etchant

Mechanical Grooving:

The method of mechanical grooving is used when uniformity is required in groove shapes. The grooves are fabricated by an electric diameter cutter. As the surface of the disc of rotated, the guider ring steers the cutter, in this way required shape of the groove is formed. A relative disadvantage of mechanical grooving process is that it requires very specialized machinery for the groove fabrication.

Soldering:

When conventional and common used grooving methods are inappropriate for the specific job in particular, method of soldering is used for groove fabrication. In this method, foil or metal sheet is taken on which the grooves are already etched is taken and then soldered on to the work piece or bearing. However, there are some factors which need to be kept in eye in the soldering method of groove fabrication. Some these are listed below:

- Temperature at which the bearing is to be operated

- The geometry and sizes of the bearings
- Nature and properties of the materials to be joined by soldering

Laser Machining:

This is a relatively modern process of groove fabrication in which laser technology is used to fabricate grooves on work pieces or bearings. It is also a very complicated method to apply as it is imperative to keep in check the molten metal properties. Hence, very complex calculations are required to achieve required depth before attempting the fabrication of grooves.

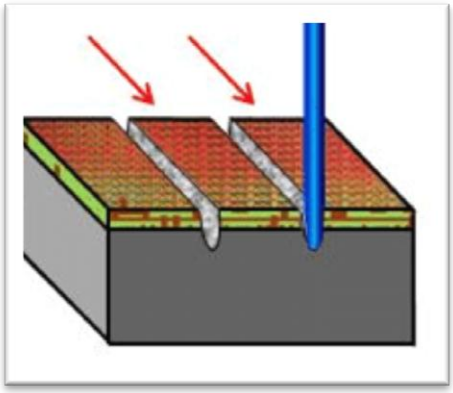


Fig 1.1: Laser Machining

The process which is used in this thesis work for fabrication of grooves is Electro chemical etching through photo fabrication.

Photo-fabrication:

Photo fabrication is a technique of working metals and nonmetals with the aid of photography and chemicals. At the heart of this method are photo sensitive resists which are solutions of resins in organic solvents which become light sensitive when applied in a coating to the chosen material and dried. After exposure to ultra violet light, the unwanted areas of the resist coating are removed by the developer, leaving a resist pattern which possesses extremely high chemical resistance.

Types of Photo sensitive Resists:

There are two types of photo sensitive resists.

1. Negative working

2. Positive Working

Negative Working Photo Sensitive Resists:

In negative working photo sensitive resists, the exposed areas of the resist remain on the surface after development to form the stencil.

Positive Working Photo Sensitive Resists:

In positive working photo sensitive resists, the unexposed areas of the resist remain on the surface after development to form the stencil.

Working of Photo sensitive Resist:

When exposed to ultra violet radiation through a photographic transparency, a negative working resist polymerizes in the areas that are struck by the ultra violet radiation. The image formed by the ultra violet radiation and defined by the clear areas of transparency is insoluble in the developing bath. The opaque areas of the transparency act as a mask and allow those portions that have received no exposure to be dissolved in the developer. The soluble portions wash away and leave a tough, chemically resistant image on the surface. This image acts as a clearly defined mask for etching, plating or some other form of surface alteration.

In positive working photo sensitive resists, ultra violet radiation striking the surface will render that layer soluble. The unexposed resist areas are insoluble in the resist developer. Positive resists will require a transparency with image the reverse of those used for exposure of negative resists producing similar results in the final surface treatment.

Electro Chemical Etching:

Using an etchant to remove exposed portions of the metal electro chemically, after it has been masked is called Electro chemical etching. Photo sensitive resists form a barrier to the penetration of etchant when they are suitably exposed and processed. Photographic techniques allow production of precise parts and provide methods for making each part the same as the last. Electro chemical etching is especially useful for working metals and foils where physical action might distort, set up strain in, or otherwise change the character of the metal. With this process, thin or brittle metals can be worked and the process yield remains high.

1.1 Background and Motivation

1.1.1 Literature Review:

Sekar T. et al. [1] had studied the improvement of ECM (electrical chemical machining) using three jets (circular, spiral, square) with rotating tools. It was found that parameters feed rate, energy configuration, energy consumption improves effectively material removal rate under rotating and stationary tool condition while machining on AISI 1035 carbon steel with best results for rotating tool for all jet configuration.

E.S. Lee et al [2] had experimented electrochemical machining on hydrodynamic bearing for micro grooves with aqueous sodium chloride gives better results than the aqueous sodium nitrate in case of surface roughness profile considered as process parameter. Microgrooves precisely control had been done for homogeneous current distribution cathode while non-conducting part developed. A PECM process prototypical to foresee the machining depth had been established for the investigation of the inter-electrode gap.

Orhan Çakır [3] in 2007 in had experimented micro machined processof stainless steel material by chemical etching method. Ferric chloride was selected as etchant with four different etchant concentrations at various etching temperature and influence by adding hydrochloric acid to main etchant on etching performance was examined. Objective was to explore the depth of etch, surface roughness affected by etchant concentration, hydrochloric acid addition and etching temperature. Results were etching temperature for any etchant concentration is important factor in case of depth of etch and surface roughness. Moreover, adding of HCL to main etchant enlarged depth of etches at any etching temperature.

K.P.Rajurkar et. al. [4] in 2005 had studied the inter-electrode gap improvement for pulse electrochemical machining which was limited by electrolyte boiling. The results indicates that gap size and filtered current signal variance are directly correlated with maximize at shorter pulse.

H.S. Shin et. al. [5] investigated Electrochemical etching using laser masking for stainless steel and anodic dissolution process to get stable process conditions. In the process three storied tower & array were made-up successfully. Lastly, a deep void with a depth of 55 mm was fabricated by multi step process.

Xiong Lu et. al [6] were the researcher interested to find out results of electrochemical machining on titanium for bio-medical applications. Two kind of process were implemented namely electrochemical micromachining and jet-electrochemical micromachining second

named process can machine surfaces with any type of curvature, and is not limited to flat surfaces as first one. Jet-electrochemical micromachining is most effect method of these two processes.

B. Bhattacharyya et. al. [7] in research named Experimental study on electrochemical micromachining. Process constraints studies micro-tool feed rate, electrolyte flow, and pulse period and pulse on–off ratio successfully at favorite values during all collections of experiments. The detail examination of micro-sparks in the machining gap with the assistance of digital storage oscilloscope and waveform viewer software along with SEM micrographs of the machined micro-holes create the fact the selection of best parametric setting is vital to achieve higher machining accuracy with better surface integrity of the micro-machined products.

1.1.2 Research Objectives

The aim and objective of this research is to optimize the Electro chemical etching process for the fabrication of micro depth grooves or slits on ASTM 52100 or 100Cr6 Bearing steel. This optimization procedure includes the careful approximation of time required for a Bearing steel sample with given stencil impression on its surface to reach the required depth of 10 micron, with several different combinations and variations of electrolyte concentration, current and solution temperature.

Further the Bearing steel samples which achieve the required depth of 10 micron are to be analyzed for its surface area roughness value (S_a) on an Atomic Force Microscope, with the smoothest Bearing steel samples considered the most optimum.

After measuring surface area roughness value (S_a) on an Atomic Force Microscope, Bearing steel samples are to be cross sectioned on a wire cut machine and carefully analyzed and observed on an optical microscope for the measurement of Kerf angle, with Kerf angle closest to 90 degree considered the most optimum.

Chapter - 2: Experimentation Procedure and Design of Experiments

2.1 Process Outline:

The method of groove fabrication used in this work is electro chemical machining through photo fabrication. Photo fabrication processes have in common the use of a line transparency and a photo resist coated surface. The resist, when exposed and developed forms a stencil, which confine further chemical operations to the unprotected portions of the surface. The typical photo fabrication process proceeds with these steps:

1. Preparation of master drawing or art work.
2. Produce a film transparency from the art work for photo resist exposure control.
3. Prepare and coat a surface with photo resist.
4. Expose the photo resist surface, controlling the area of exposure with transparency.
5. Process the resist to form a stencil.
6. Proceed with etching of electroforming.

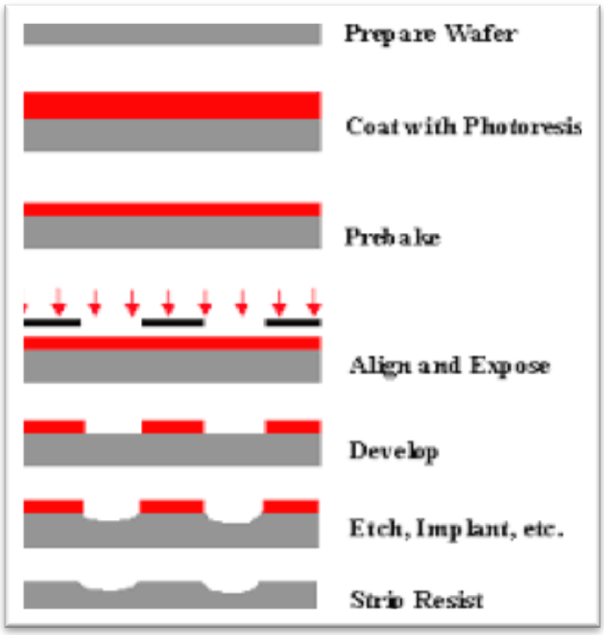


Fig 2.1: Steps of Photo-fabrication

2.2 Applications:

Photo fabrication has numerous applications, including the following:

- Printed circuits
- Thin film circuits
- Integrated circuits
- Chemically machined metal parts
- Nameplates
- Reticles, grids, scales, rulers
- Decorative designs
- Litho-plates
- Weight reduction

2.3 Surface Roughness:

Whenever we notice a surface, we notice the difference in its appearance from other surfaces, as in the surfaces are shiny or dull and rough. These changes in appearances are due to surface roughness. Surface roughness of a product not only affects the product from commercial and aesthetic point of view but also its workability.

If a machine part is to be operated in contact, surface roughness is important for wear. Also if a surface is to be painted surface roughness again plays a very important role.

Since this work is focused on fabrication of micro depth grooves on Bearing steel for manufacturing of bearings, from the view of tribology we can say that the more the surface of the groove is rough, there will be more wear and more friction between the mating parts in the bearing which is not ideal for a bearing.

There are several apparatus for calculation of surface roughness like surface roughness comparator and profilometer. These come in both contact and noncontact (optical) types.

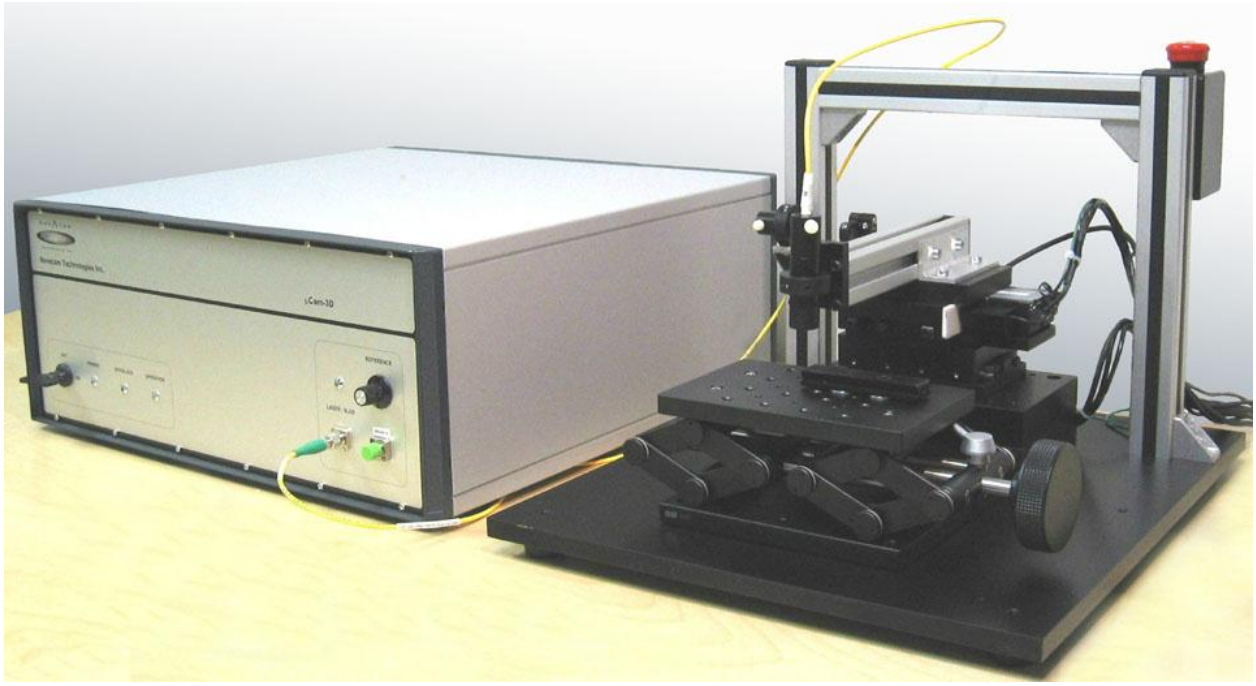


Fig 2.2: Profilometer

Roughness can be calculated for:

1. A profile or line
2. Surface or area

Measurement of roughness of a line is called profile roughness (R_a), while the extension of this profile roughness to an area is called area roughness (S_a).

In this work, we have measured Area roughness (S_a) values of micro depth grooves which was measured on an Atomic Force Microscope.

2.4 Kerf Angle:

Kerf is defined by the width of the work piece which is cut, machined or removed by a machining process.

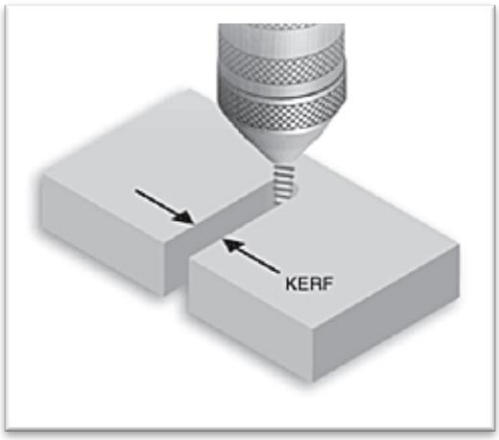


Fig 2.4.1: Kerf Width

In electro chemical machining the kerf width is the width of the stencil formed on the surface of the work piece. Since electrochemical machining is an isotropic process, that is it goes around equally in all dimensions, in addition of going through the work piece vertically downwards, the etching solution also acts on the boundaries of the stencil shaped impression formed and thus creating a taper angle instead of 90 degree angle with horizontal, called the Kerf angle.

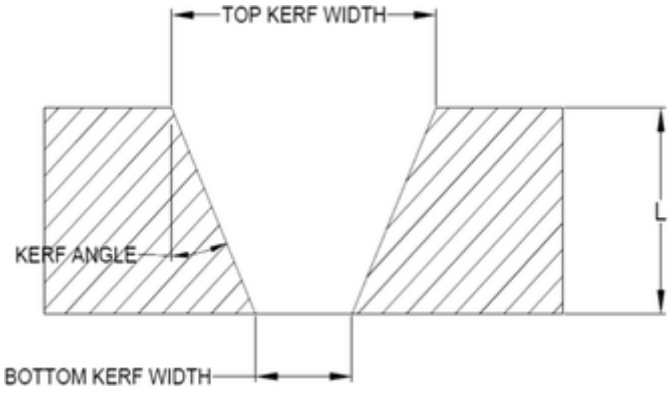


Fig 2.4.2: Kerf Angle

2.5 Experiments Layout:

Cutting off of samples on Wire cut Machine:

For fabrication of samples an 8mm diameter 100Cr6 (Bearing steel) rod was used. From this rod, numerous samples of equal thickness were cut off on wire cut machine. Wire cut machine was used for cutting off purposes so that the samples prepared were as smooth as possible and subsequently lesser time required for grinding and then polishing of the samples.

Surface Preparation:

The condition of the metal surface that receives a coating of resist is as important as the physical properties of the metal itself. Avoid metal that has been badly marred or deeply scratched. These are bothersome especially when thin resist coatings are being used. As the thin coating dries, it tends to bridge the scratch. This leaves the bottom of the scratch unprotected, and a tiny capillary that can actually retain etching solution forms. As etching progresses, this capillary will open up more and cause a loss in quality or a ruined part.

The cleaning cycles used prior to coating with a photo sensitive resist must be effective. Under cleaning a surface will often resist in complete photo resist failure. Over cleaning will not usually result in failure, but may change the surface properties of the metal. Thus, the different kinds of surface contamination must be analyzed and the most effective way of removing them found.

Grinding and Polishing:

After cutting off, samples were ready for grinding and polishing. Grinding is a necessary process prior to polishing and hence these samples were ground on a grinding machine. After grinding, these samples were polished using Alumina grate of 1 micron size.

Vapour Degreasing:

After polishing, the next step was getting rid the samples of all impurities (oil, grease) or slug that may have adhered to the surface of the samples during handling, cutting, grinding or polishing. For this purpose, vapour degreasing of the samples was performed.

In vapour degreasing samples were put in a container in a tray and beneath the tray was a chemical usually Isopropyl alcohol. This container was then put on a hot plate to boil Isopropyl alcohol. Isopropyl alcohol boiled, its vapours rose and condensed on the lid of the container and started to condense. These condensing vapours fell on the Bearing steel samples and took the impurities, oil and grease with them on the way down. In this manner the 100Cr6 samples were vapor degreased.

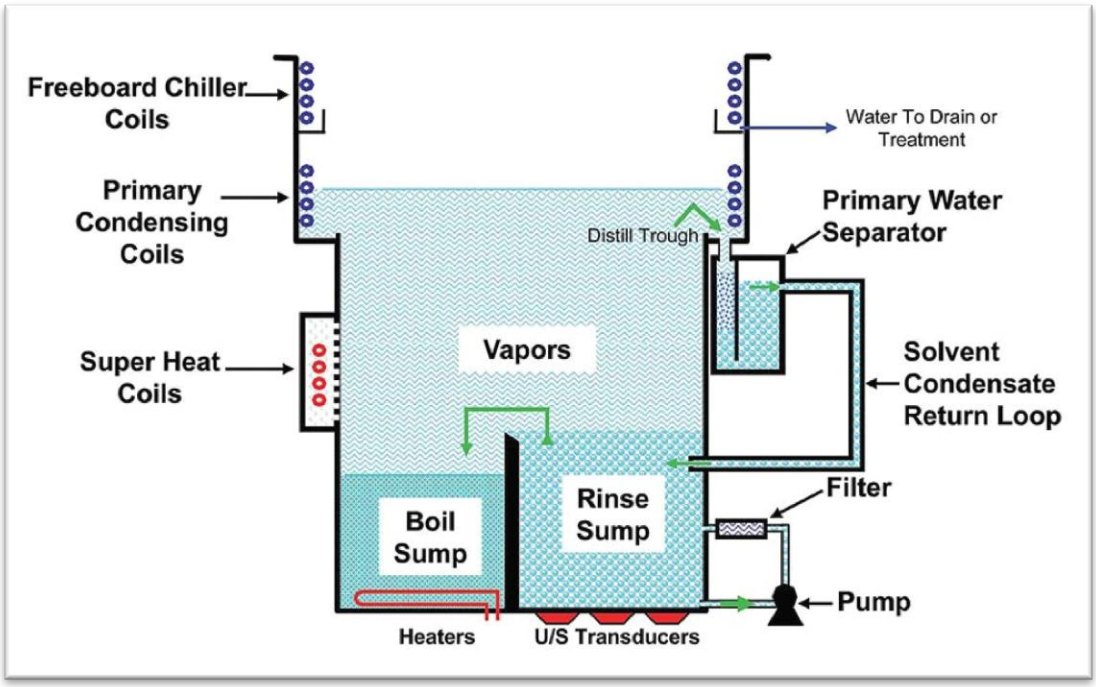


Fig 2.5.1: Vapour Degreasing

Ultrasonic Cleaning:

Since these experiments were meant to be very precise in way that 10 micron depth was to be achieved through electrochemical machining, cleaning of the sample held a prime importance in the whole process. Even the minutest sized particle of impurity or dust particle could have easily adhered to the surface of the Bearing steel samples to be etched and sabotaged the process. For this purpose, after vapour degreasing, ultra sonic cleaning of bearing steel samples was performed.

Ultra sonic cleaner uses ultrasonic waves and vibrations to remove minute particles hiding or adhered to the ultra-small recesses pores in the work piece.

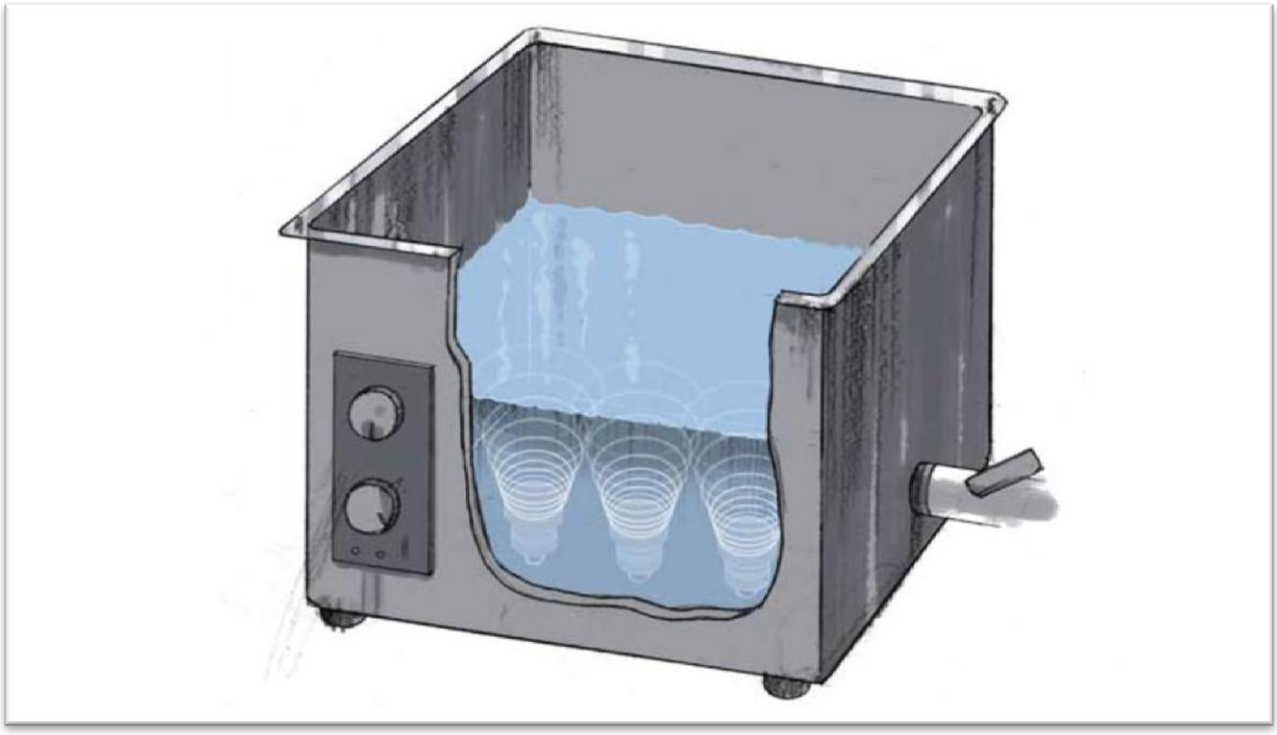


Fig 2.5.2: Ultra Sonic Cleaner

Photo Resistive Material Coating:

The Bearing steel samples, which were now polished and cleaned thoroughly, were then ready for photo resistive chemical coating. This was performed through dip coating.

Dip Coating:

Dip coating is the simplest method for coating thin metal foils and other miniature parts. Simply immerse the cleaned metal work piece in the resist, with draw, and hang the coated metal up to dry in a dust free area.

Resist coatings produced by simple dipping are always wedge shaped, with the thin end of the coating at the point where the work was hung up to dry. For some applications, this may be of no concern. For others, however, wedging may interfere with process reliability. If wedging is a problem, it can be partially overcome by recoating the work piece a second time but in the opposite direction. After coating, hang the work with the thicker end of the first coating uppermost.

Each cleaned sample was dipped in a small flask or beaker containing the photo resistive chemical and kept in a clean room for drying for twenty-four hours.

Samples were then ready for exposing to ultra violet light for the formation of impression which was to be etched.

Ultra Violet Light Exposing:

The photo resistive chemical coated samples were then exposed, in a clean room, to ultra violet light whose source was Xenon lamp of 150-watt power. The impression of slit or groove was projected via X-ray sheet which had the impression cut out on it previously. After confirming on an optical microscope that proper exposing had taken place, the Bearing steel samples were then taken for developing.

Developing:

After exposing of bearing steel samples to ultra violet light in a clean room, next step was to develop the impression of the groove or slit formed on the samples via ultra violet light coming through an X-ray sheet.

This process was again performed in a clean room and chemical used for developing the impression was EP-33 which was basic in nature having pH value of 13.

After developing the impression, the samples were just soaked in water to remove the developed impression of photo resistive chemical coating. The Bearing steel sample was now bare in the place of impression of groove or slit while rest of the sample remained coated, so that when sample would have been dipped in the HCl solution for etching, only the slit or grooved portion would have been exposed to the chemical and the rest of the sample would remain un-touched.

Electrochemical Machining /Etching:

After development of bearing steel samples, they were ready to be electro chemically machined. For this purpose the parameters or factors of electro chemical machining which were chosen to be variable to get 10 micron depth were:

1. Electrolyte concentration (%HCl volume by volume)
2. Current (mA)
3. Temperature of solution (°C)

2.6 Design of Experiments:

Each factor was varied four times, i.e. level of the design was four. The values four varied factors of the experimentation are given below:

No. of factors: 3

1. Etchant Concentration (% HCl v/v) (6%, 8%, 10%, 12%)
2. Current (mA) (50, 55, 60, 65)
3. Temperature (°C) (25, 35, 45, 55)

No. of levels: 4

Orthogonal Array: L16

Table 2.6.1: Taguchi L16 Array

Sr. No.	Etchant Concentration (%HCl v/v)	Current (mA)	Temperature (°C)
1	6	50	25
2	6	55	35
3	6	60	45
4	6	65	55
5	8	50	35
6	8	55	25
7	8	60	55
8	8	65	45
9	10	50	45
10	10	55	55
11	10	60	25
12	10	65	35
13	12	50	55
14	12	55	45
15	12	60	35
16	12	65	25

Outcomes or responses which were to be measured after achieving 10 micron depth of each sample were:

1. Time taken (seconds) to get to 10 micron depth of slit or groove in the sample
2. Area roughness of etched surface (nm)
3. Kerf Angle of slit or groove edges (degrees)

Time Measurement:

Time taken for each of these experiments for the Bearing steel samples to achieve a depth of 10 micron of slit or groove, by varying different combinations of Etchant Concentration, Current and Temperature was measured using hit and trial method and checking depth of each sample after every experiment on a Talyrond 100 apparatus.

The time taken for each sample's slit or groove to reach approximately 10 micron depth is shown in the table below:

Table 2.6.2: Time Measurements

Sr. No.	Sample No.	Etchant Concentration (%HCl v/v)	Current (mA)	Temperature (°C)	Time for 10um Depth (sec)
1	9	6	50	25	55
2	10	6	55	35	52
3	11	6	60	45	45
4	12	6	65	55	44
5	2	8	50	35	50
6	1	8	55	25	49
7	3	8	60	55	48
8	4	8	65	45	47
9	7	10	50	45	45
10	8	10	55	55	44
11	5	10	60	25	40
12	6	10	65	35	37
13	16	12	50	55	50
14	15	12	55	45	40
15	14	12	60	35	35
16	13	12	65	25	32

Depth Measurement:

The Bearing steel sample was placed on the round table of Talyrond 100. After ensuring that the Bearing steel sample was entirely lying flat on the holding fixture, the sample was firmly held in its place by synthetic clay. Then the stylus of the Talyrond 100 machine with needle tip was brought over the Bearing steel sample. The needle tipped stylus was then slid across the slit or groove in the sample. The Talyrond 100 detected the depth of the slit or groove in the sample by detecting the high and low surfaces through contact by needle tipped stylus.

Fig 2.6.1: Talyrond 100

Roughness Measurement:

Each sample for which the target depth of slit or groove of 10 micron was approximately achieved was then analyzed on Atomic Force Microscope. An Atomic Force Microscope was used for observation of surface morphology of provided work piece in the range of Nano

meters.

Fig 2.6.2: Atomic Force Microscope

Atomic force microscopy or scanning force microscopy is a type of very-high-resolution scanning probe microscopy. Its resolution is in the range of fractions of a nano-meter and it is a 1000 time better than the optical diffraction limit.

The average surface area roughness values for each sample measured by the Atomic force microscope are shown in the table below:

Table 2.6.3: Roughness Measurement

Sr. No.	Sample No.	Etch. Conc. (%HCl v/v)	Current (mA)	Temp (°C)	Area Roughness, S_a (nm)			
					1	2	3	St. Dev
1	9	6	50	25	226	262	270	37.
2	10	6	55	35	413	520	525	105
3	11	6	60	45	224	319	681	244
4	12	6	65	55	450	515	550	73
5	2	8	50	35	473	509	514	36
6	1	8	55	25	459	502	515	45
7	3	8	60	55	318	531	550	211
8	4	8	65	45	400	445	450	44
9	7	10	50	45	461	499	551	55
10	8	10	55	55	502	727	750	224
11	5	10	60	25	64	80	102	23
12	6	10	65	35	357	432	861	259
13	16	12	50	55	354	540	550	183
14	15	12	55	45	176	177	362	87
15	14	12	60	35	434	479	480	43
16	13	12	65	25	236	248	359	61

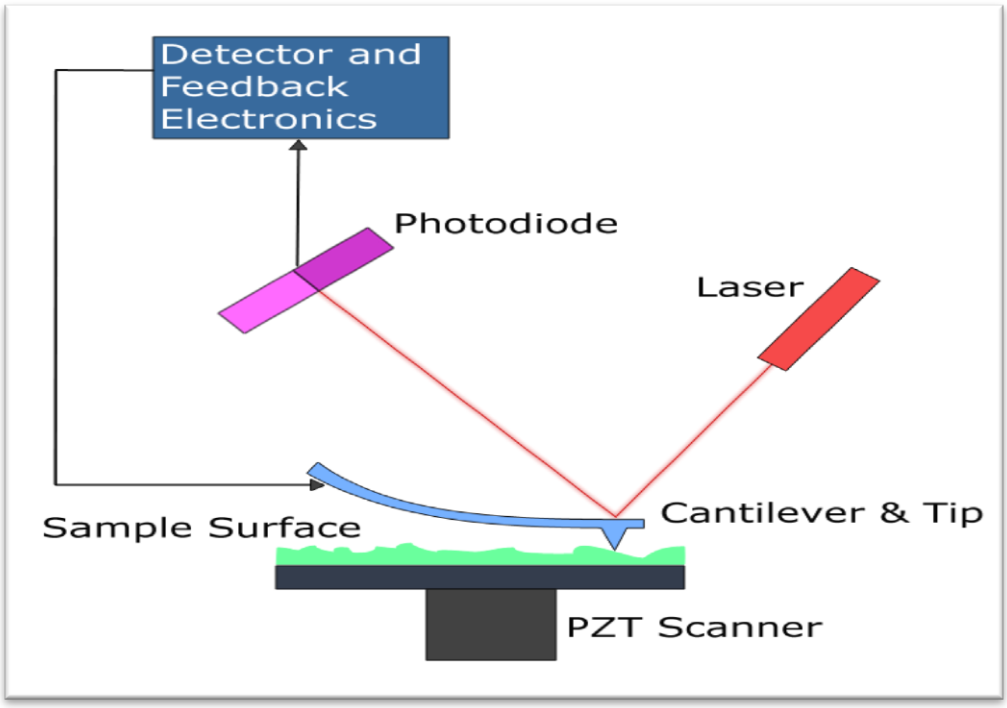


Fig 2.6.3: Principle of Atomic Force Microscope

Kerf Angle Measurement:

After measurement of area roughness on Atomic Force Microscope, next step was to measure the Kerf Angle of the slit or groove which was electrochemically machined on the Bearing steel samples. For the said purpose, the Bearing steel samples needed to be cross sectioned as the Kerf Angle would only have been visible from the cross sectioned view.

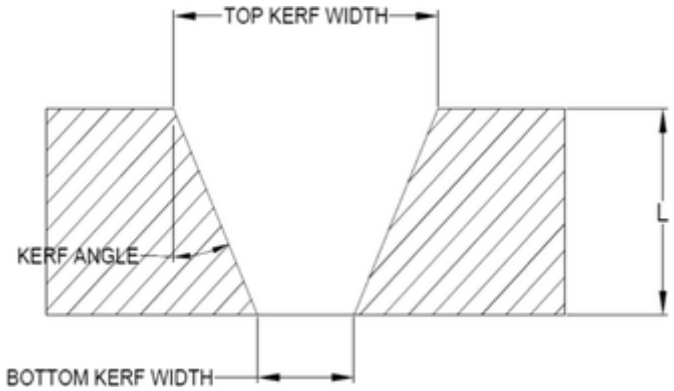


Fig 2.6.4: Kerf Angle

Wire cut machine was used to cross section the Bearing steel samples in order to minimize the bur formation. The cross sectioned sides were of the samples were gently polished on a fine polishing paper. The Bearing steel samples were then ready for observation.

After cross sectioning, the Bearing steel samples were observed on an optical microscope with attached laptop and Kerf angles of the entire cross sectioned samples were measured.

The approximate Kerf Angle values for each sample measured by the optical microscope are shown in the table below:

Table 2.6.4: Kerf Angle Measurement

Sr. No.	Sample No.	Etch. Conc. (%HCl v/v)	Current (mA)	Temperature (°C)	Kerf Angle (deg)
1	9	6	50	25	60
2	10	6	55	35	43
3	11	6	60	45	52
4	12	6	65	55	50
5	2	8	50	35	71
6	1	8	55	25	70
7	3	8	60	55	53
8	4	8	65	45	59
9	7	10	50	45	76
10	8	10	55	55	65
11	5	10	60	25	63
12	6	10	65	35	61
13	16	12	50	55	74
14	15	12	55	45	65
15	14	12	60	35	56
16	13	12	65	25	55

Pictures of Bearing Steel Samples:

Sample Coated in Photoresist

Sample Exposed and Developed

Sample Electro Chemically Machined

Sample Cross Sectioned for Kerf Angle

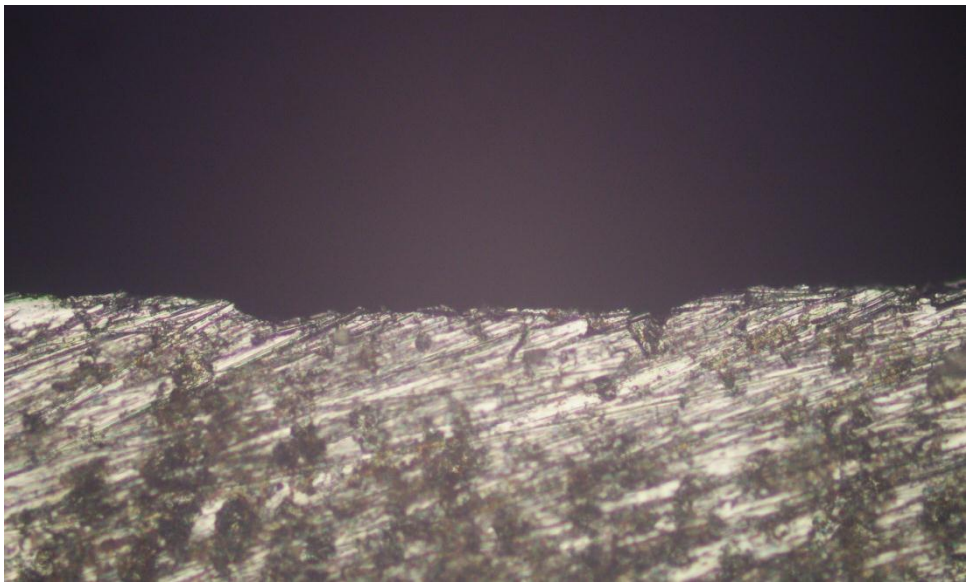
Chapter - 3: Results and Analysis

3.1 Results of Samples 1-16:

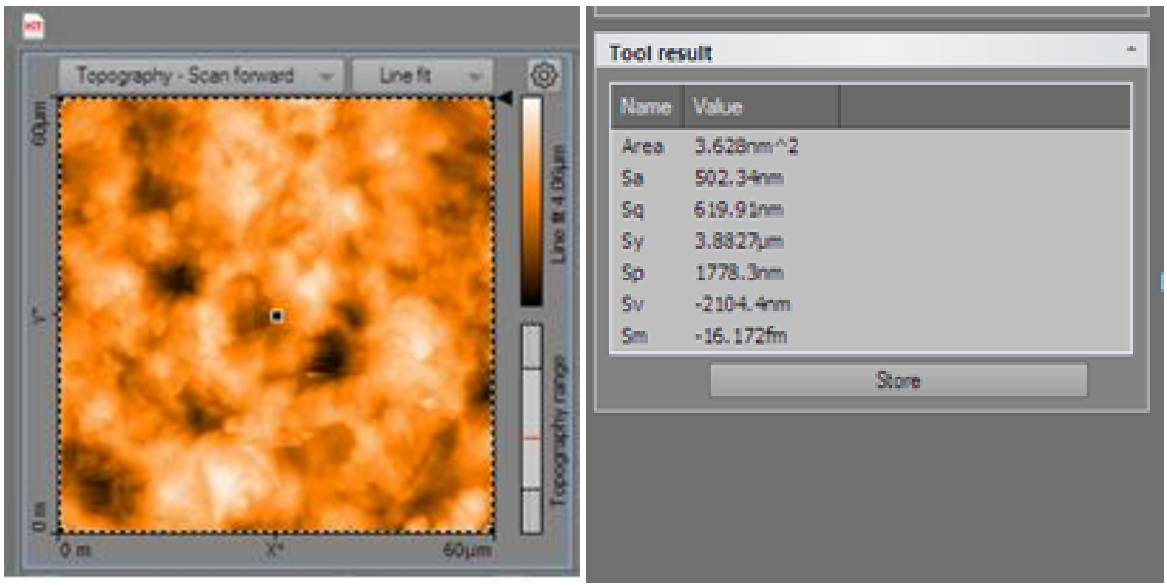
The time, surface roughness and Kerf angle measurements and images are present in this chapter.

Sample 1:

Etchant Concentration (%HCl v/v)	=	8%
Current (mA)	=	55 mA
Temperature (°C)	=	25°C
Time taken for 10 micron depth	=	49 sec
Kerf Angle measured from optical microscope	=	70°
Surface Roughness (S_a)	=	502 nm



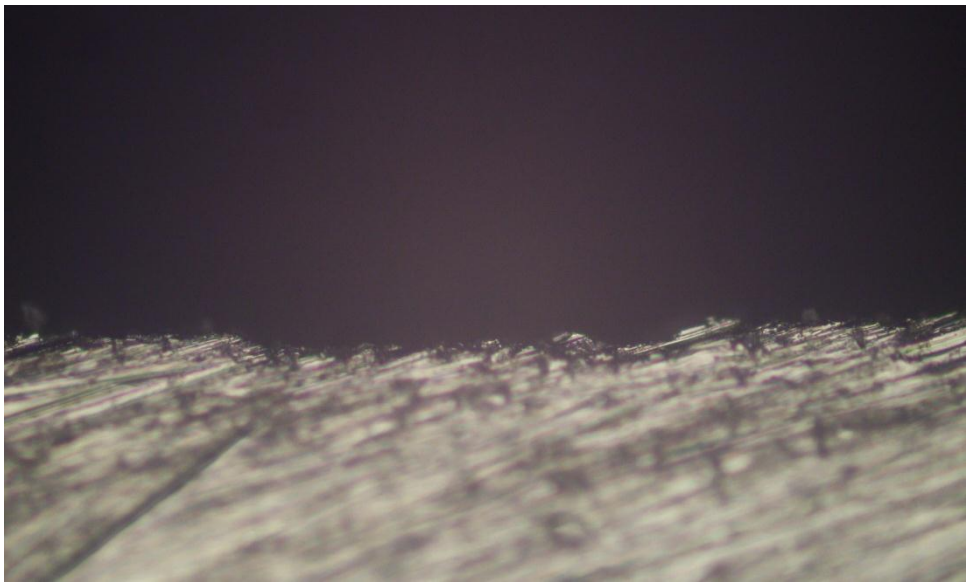
Optical Microscope Image Sample 1 (x200)



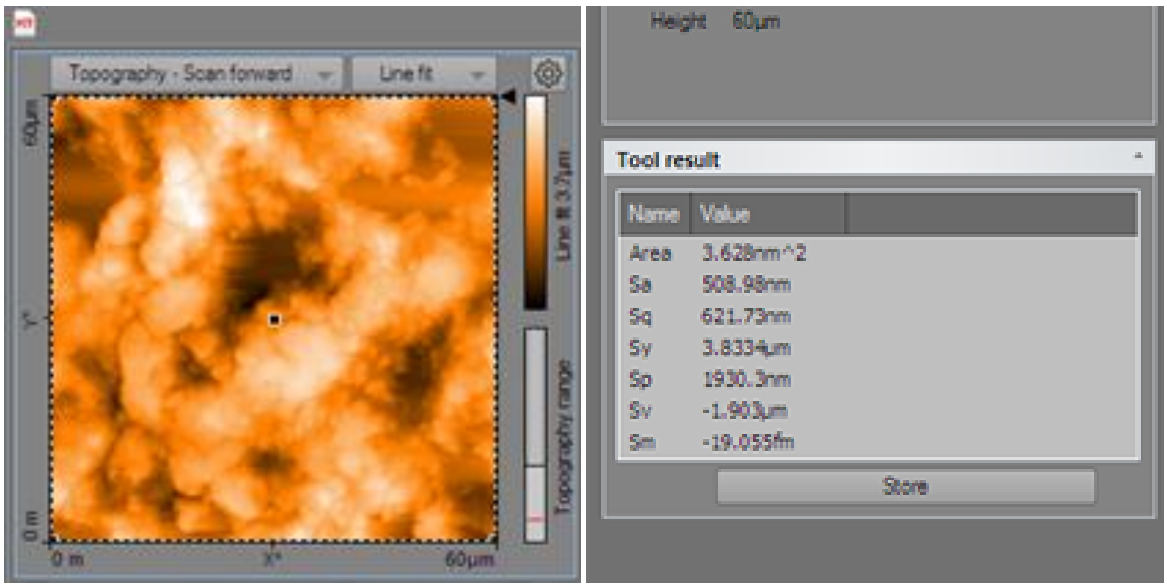
Atomic Force Microscope Results Sample 1

Sample 2:

Etchant Concentration (%HCl v/v)	=	8%
Current (mA)	=	50 mA
Temperature (°C)	=	35°C
Time taken for 10 micron depth	=	50 sec
Kerf Angle measured from optical microscope	=	71°
Surface Roughness (S_a)	=	509 nm



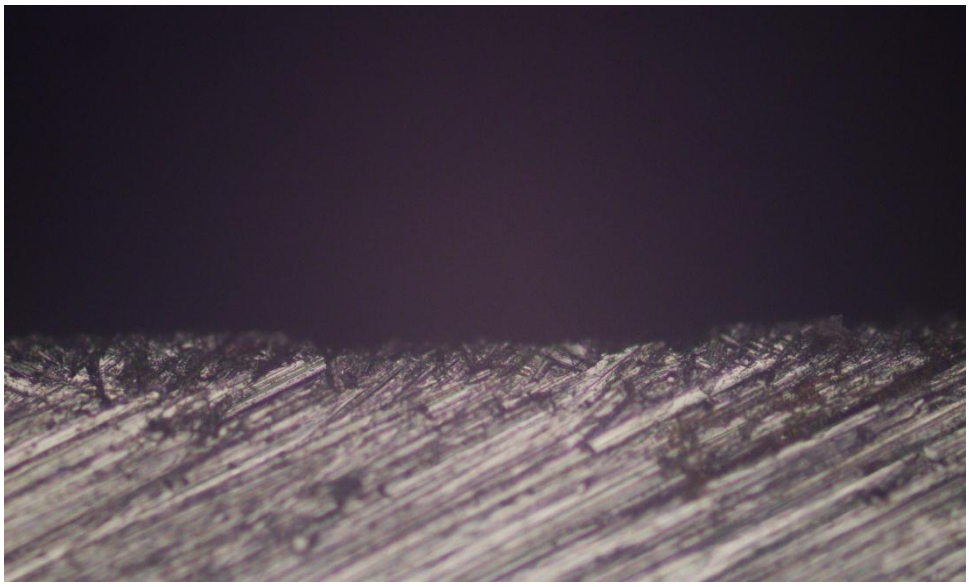
Optical Microscope Image Sample 2 (x200)



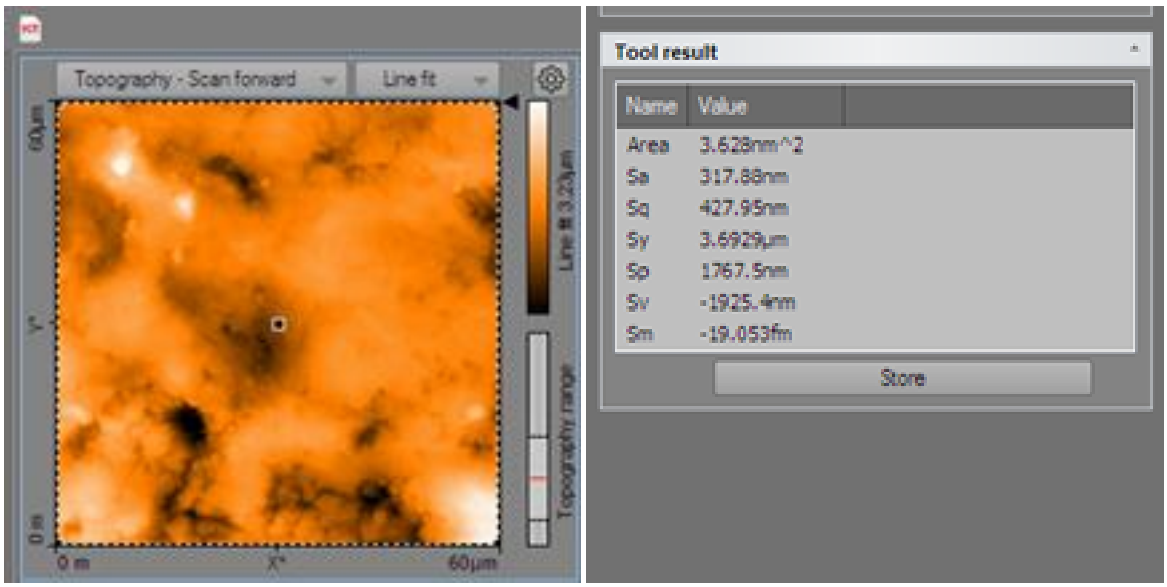
Atomic Force Microscope Results Sample 2

Sample 3:

Etchant Concentration (%HCl v/v)	=	8%
Current (mA)	=	60 mA
Temperature (°C)	=	55°C
Time taken for 10 micron depth	=	48 sec
Kerf Angle measured from optical microscope	=	53°
Surface Roughness (S_a)	=	318 nm



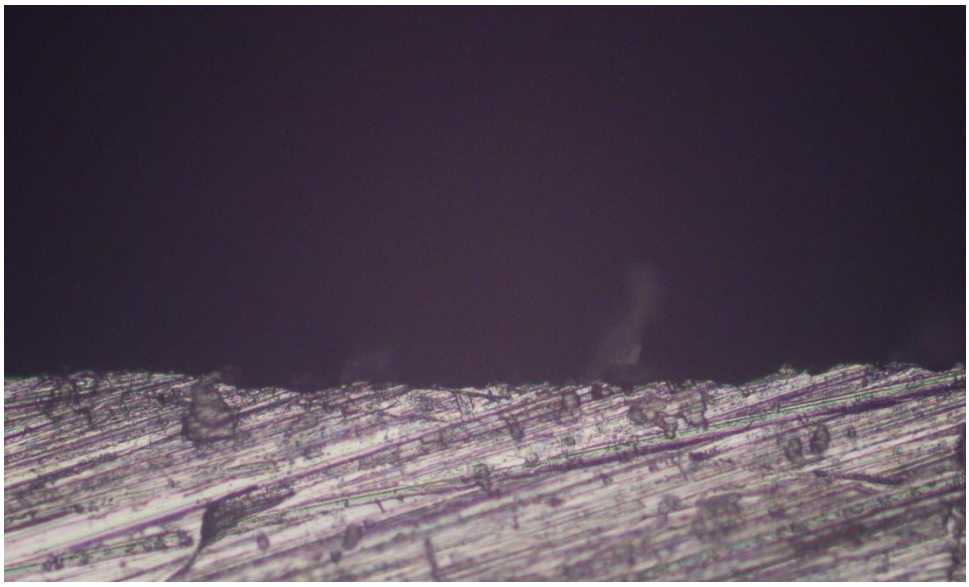
Optical Microscope Image Sample 3 (x200)



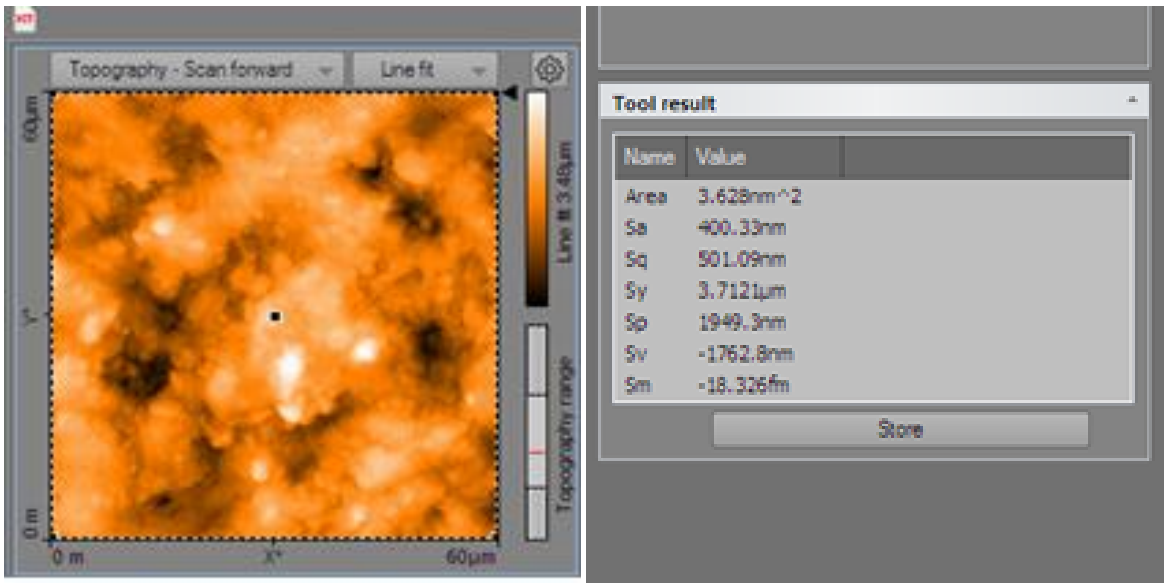
Atomic Force Microscope Results Sample 3

Sample 4:

Etchant Concentration (%HCl v/v)	=	8%
Current (mA)	=	65mA
Temperature (°C)	=	45°C
Time taken for 10 micron depth	=	47 sec
Kerf Angle measured from optical microscope	=	59°
Surface Roughness (S_a)	=	400 nm



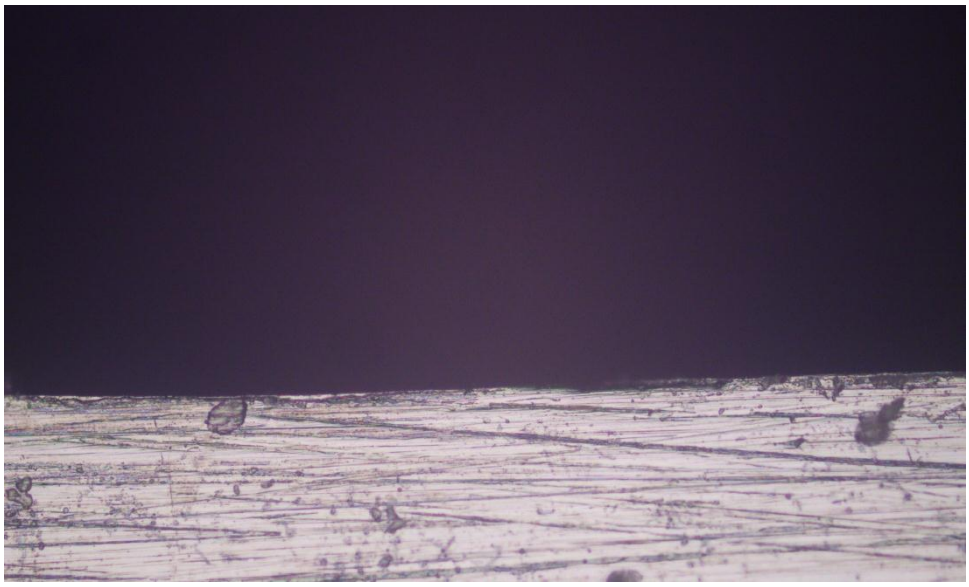
Optical Microscope Image Sample 4 (x200)



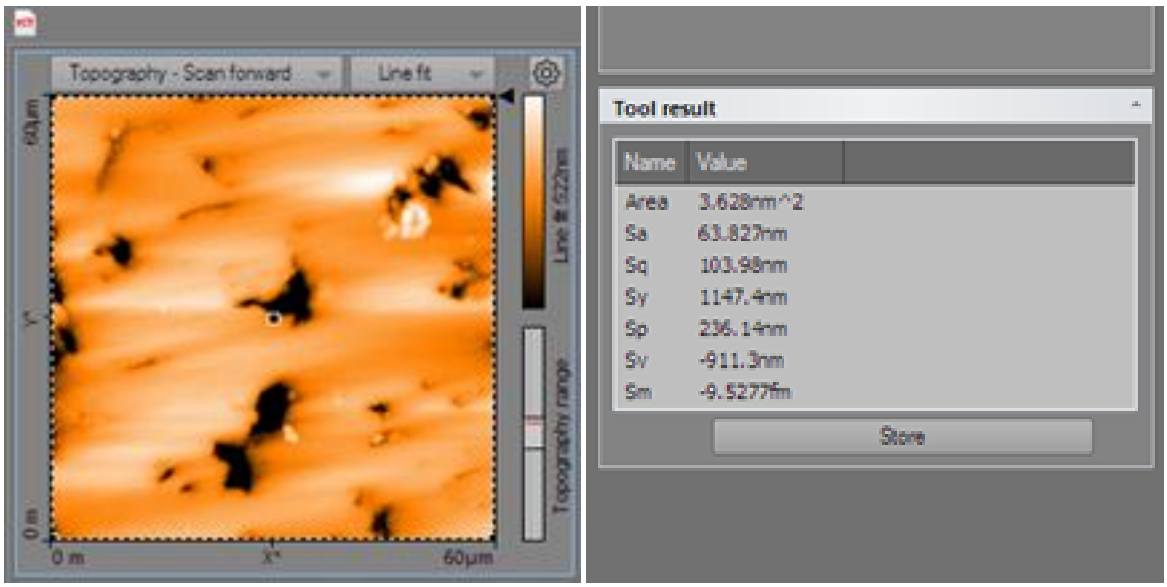
Atomic Force Microscope Results Sample 4

Sample 5:

Etchant Concentration (%HCl v/v)	=	10%
Current (mA)	=	60 mA
Temperature (°C)	=	25°C
Time taken for 10 micron depth	=	40 sec
Kerf Angle measured from optical microscope	=	63°
Surface Roughness (S_a)	=	64 nm



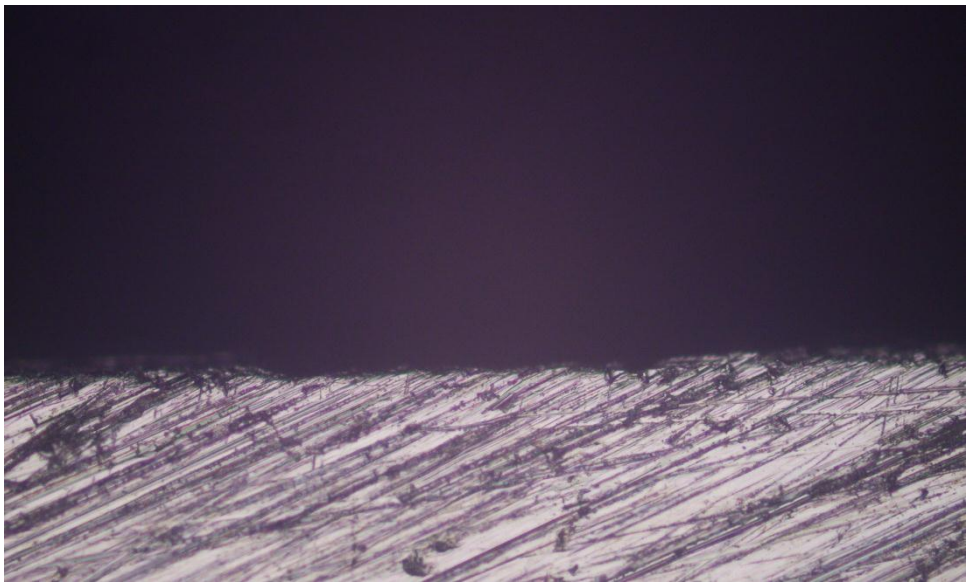
Optical Microscope Image Sample 5 (x200)



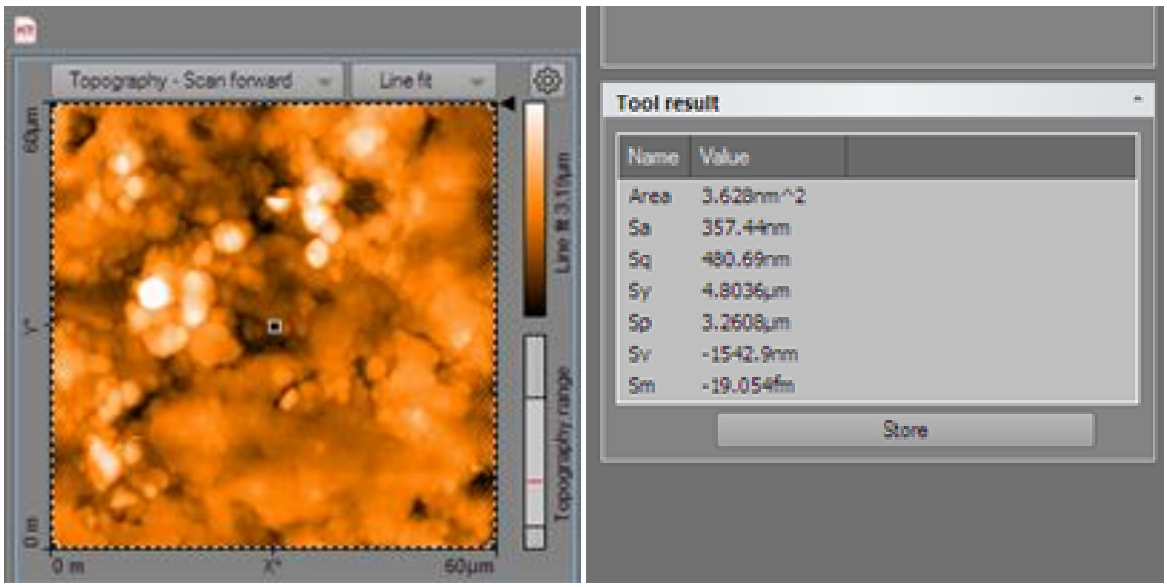
Atomic Force Microscope Results Sample 5

Sample 6:

Etchant Concentration (%HCl v/v)	=	10%
Current (mA)	=	65 mA
Temperature (°C)	=	35°C
Time taken for 10 micron depth	=	37 sec
Kerf Angle measured from optical microscope	=	61°
Surface Roughness (S_a)	=	357 nm



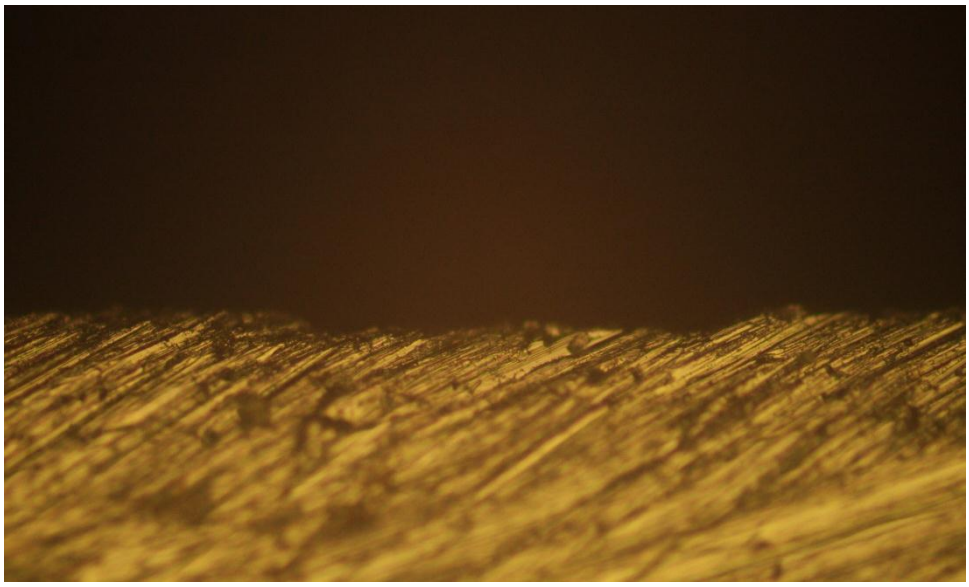
Optical Microscope Image Sample 6 (x200)



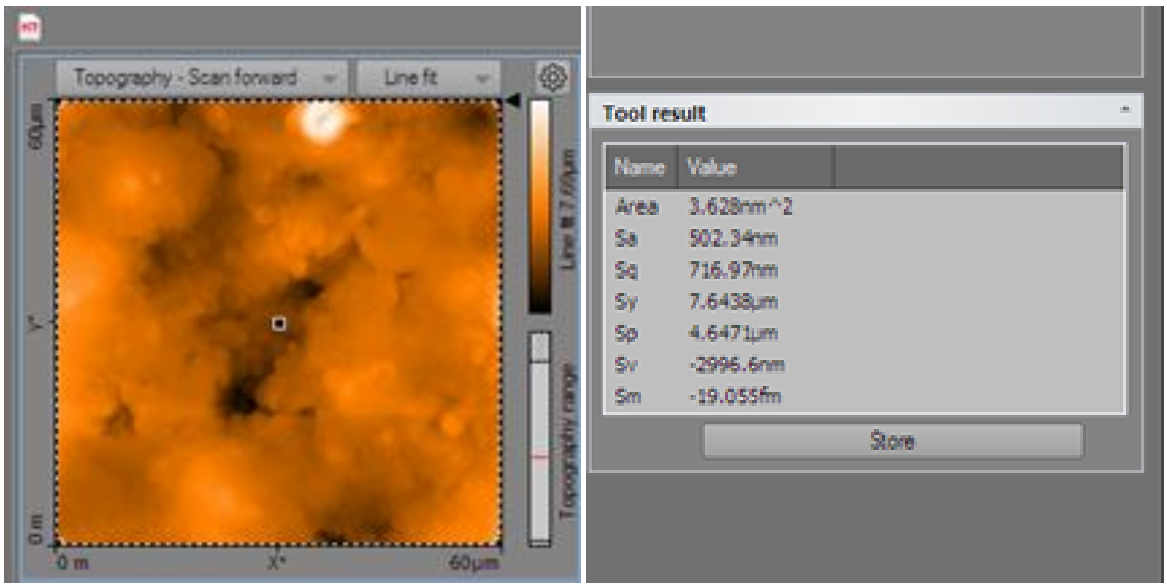
Atomic Force Microscope Results Sample 6

Sample 7:

Etchant Concentration (%HCl v/v)	=	10%
Current (mA)	=	50 mA
Temperature (°C)	=	45°C
Time taken for 10 micron depth	=	45 sec
Kerf Angle measured from optical microscope	=	76°
Surface Roughness (S_a)	=	502 nm



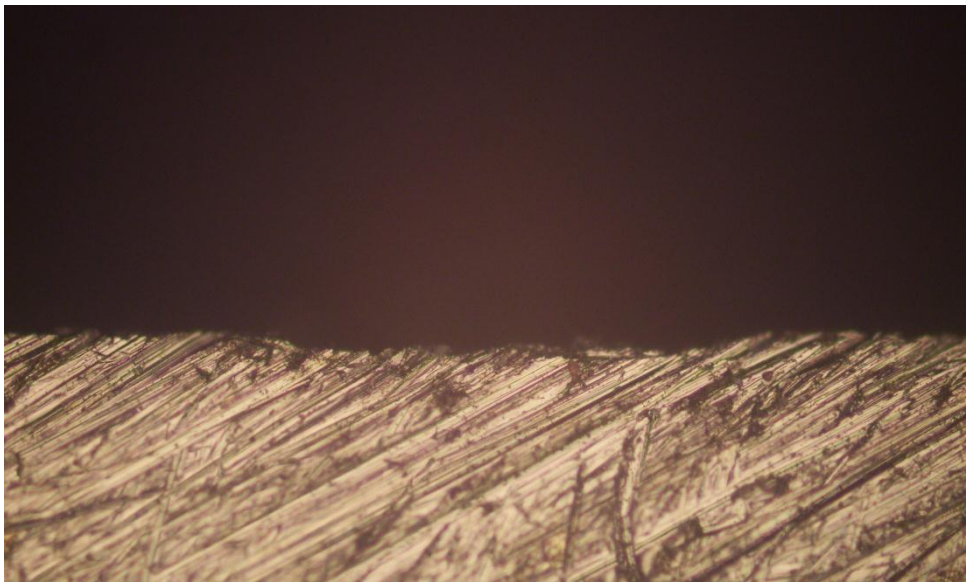
Optical Microscope Image Sample 7 (x200)



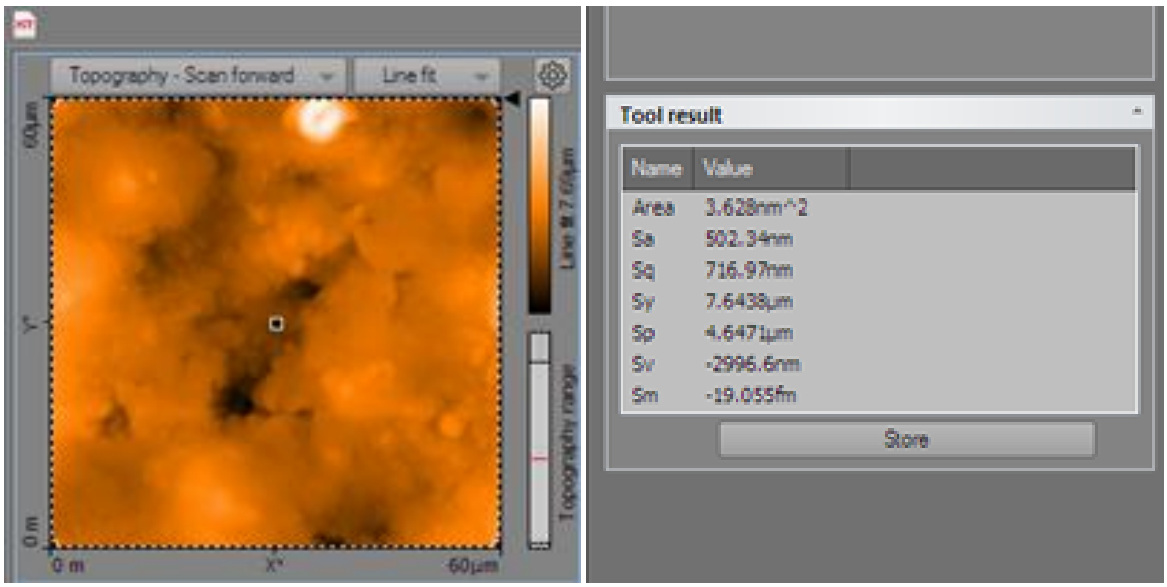
Atomic Force Microscope Results Sample 7

Sample 8:

Etchant Concentration (%HCl v/v)	=	10%
Current (mA)	=	55 mA
Temperature (°C)	=	55°C
Time taken for 10 micron depth	=	47 sec
Kerf Angle measured from optical microscope	=	65°
Surface Roughness (S_a)	=	502 nm



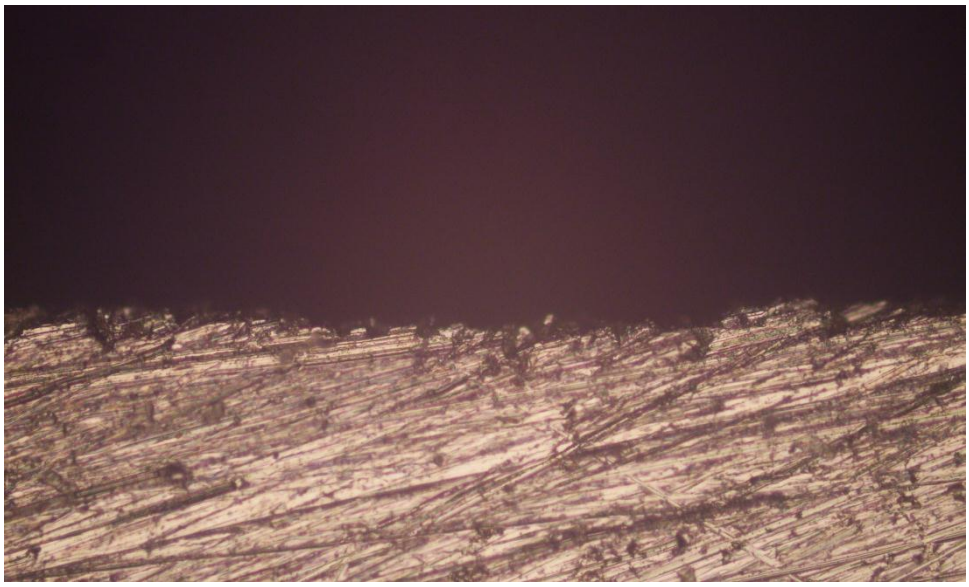
Optical Microscope Image Sample 8 (x200)



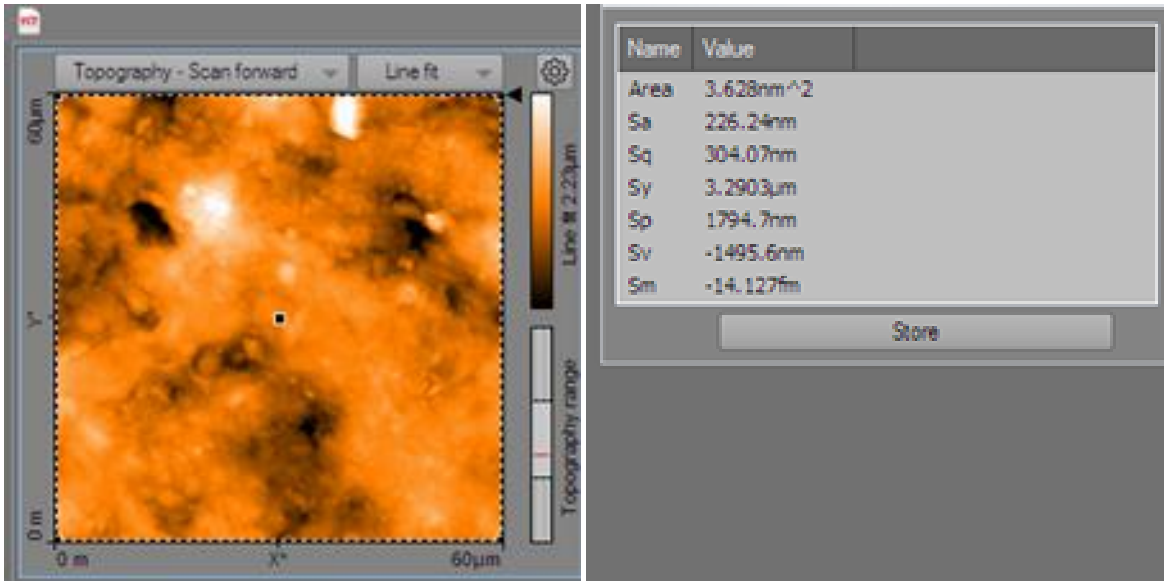
Atomic Force Microscope Results Sample 8

Sample 9:

Etchant Concentration (%HCl v/v)	=	6%
Current (mA)	=	50 mA
Temperature (°C)	=	25°C
Time taken for 10 micron depth	=	55 sec
Kerf Angle measured from optical microscope	=	60°
Surface Roughness (S_a)	=	226 nm



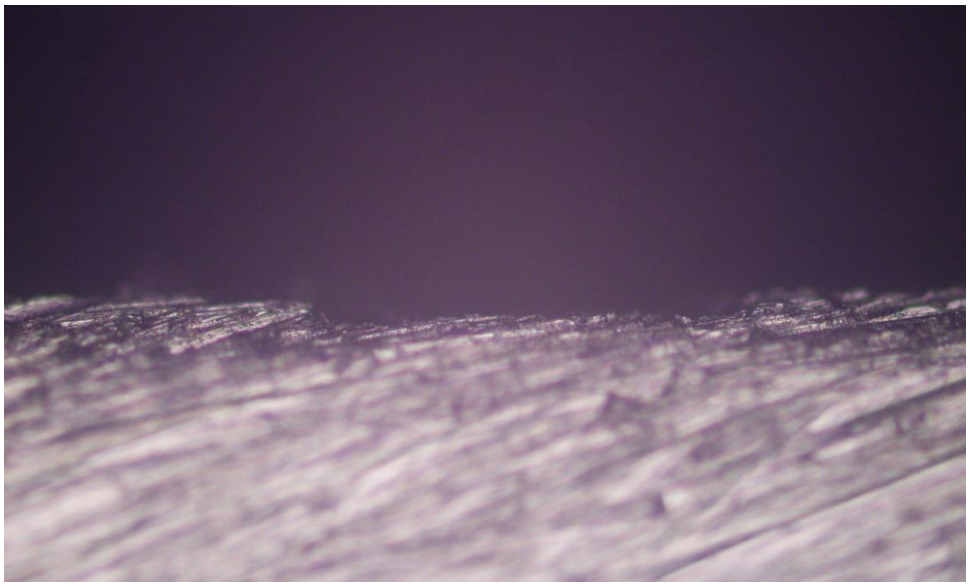
Optical Microscope Image Sample 9 (x200)



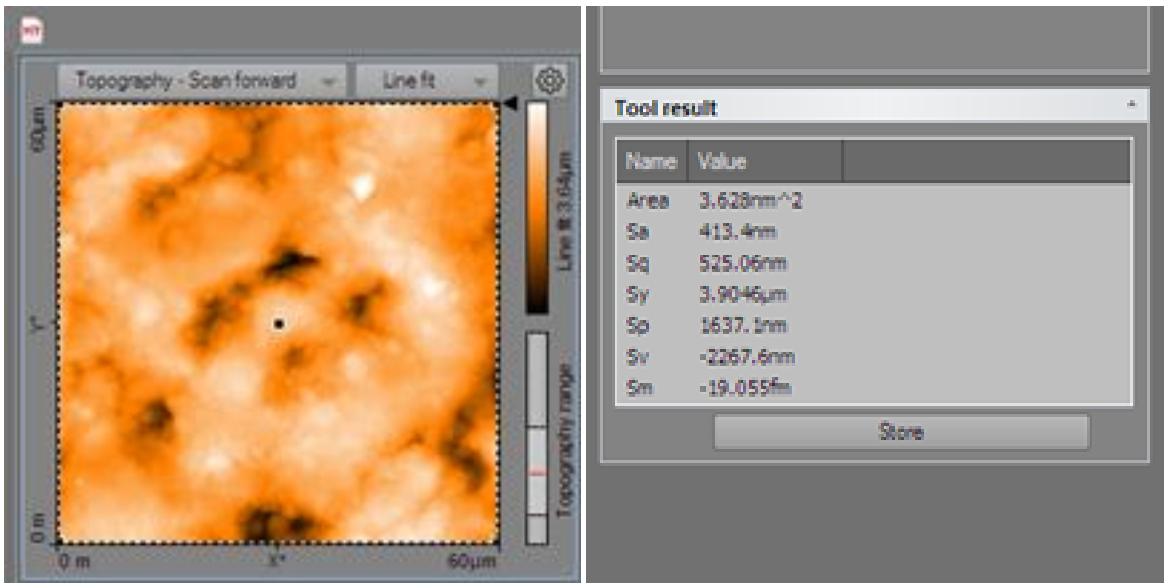
Atomic Force Microscope Results Sample 9

Sample 10:

Etchant Concentration (%HCl v/v)	=	6%
Current (mA)	=	55 mA
Temperature (°C)	=	35°C
Time taken for 10 micron depth	=	52 sec
Kerf Angle measured from optical microscope	=	43°
Surface Roughness (S_a)	=	413 nm



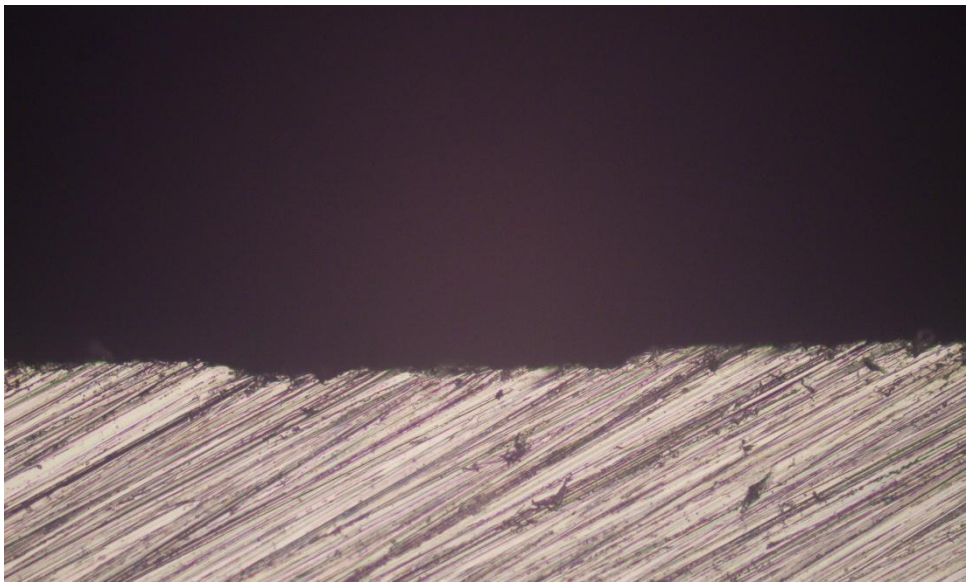
Optical Microscope Image Sample 10 (x200)



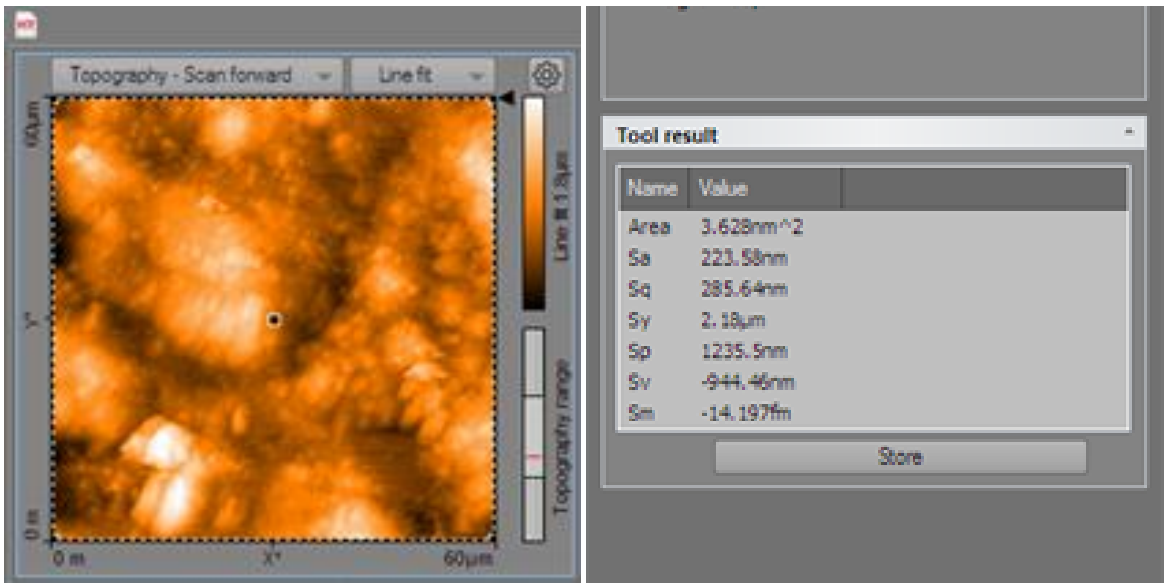
Atomic Force Microscope Results Sample 10

Sample 11:

Etchant Concentration (%HCl v/v)	=	6%
Current (mA)	=	60 mA
Temperature (°C)	=	45°C
Time taken for 10 micron depth	=	45 sec
Kerf Angle measured from optical microscope	=	52°
Surface Roughness (S_a)	=	224 nm



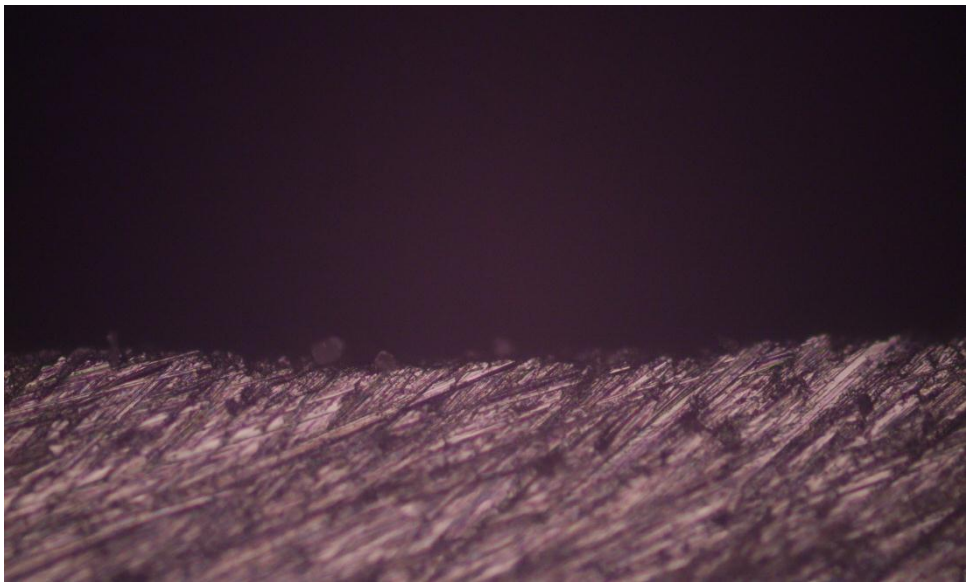
Optical Microscope Image Sample 11 (x200)



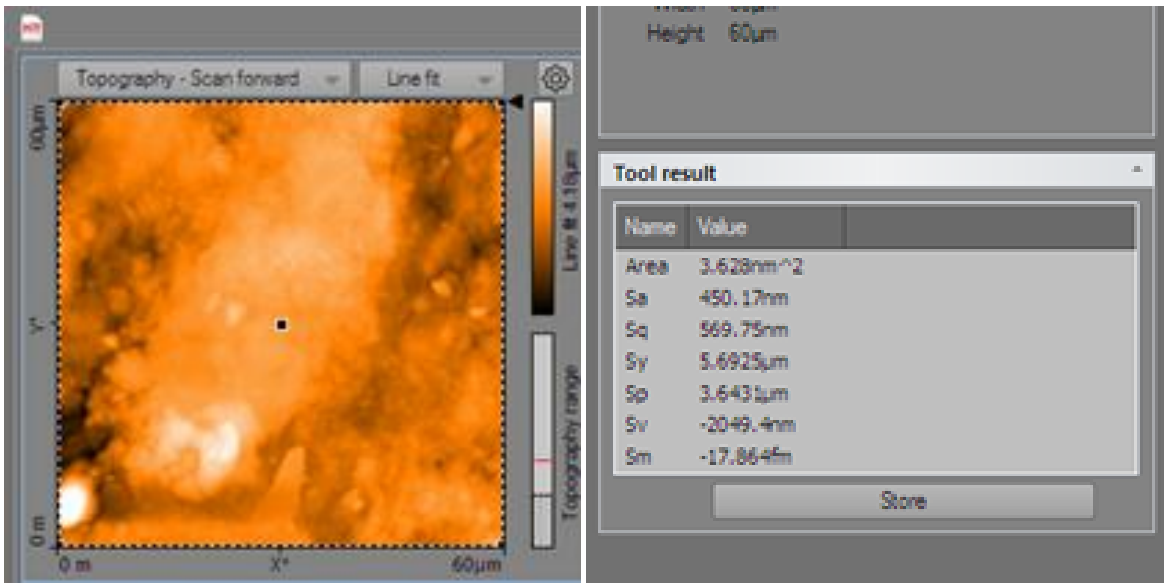
Atomic Force Microscope Results Sample 11

Sample 12:

Etchant Concentration (%HCl v/v)	=	6%
Current (mA)	=	65 mA
Temperature (°C)	=	55°C
Time taken for 10 micron depth	=	44 sec
Kerf Angle measured from optical microscope	=	50°
Surface Roughness (S_a)	=	450 nm



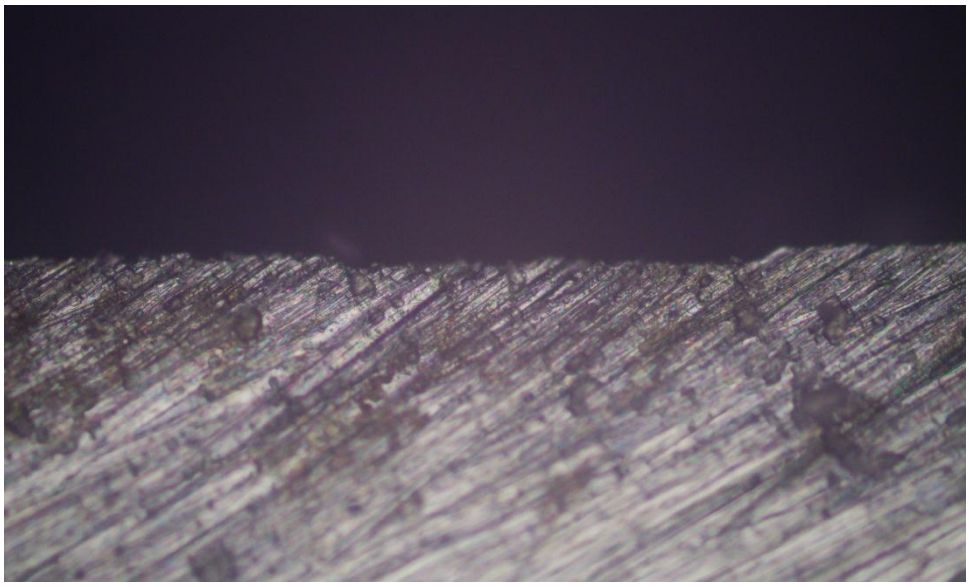
Optical Microscope Image Sample 12 (x200)



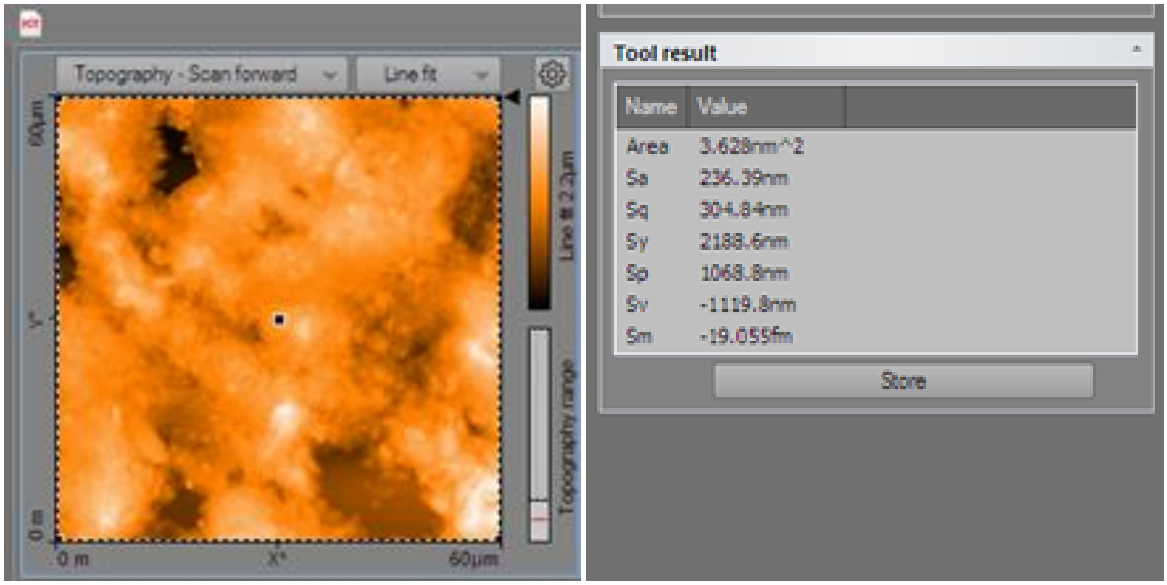
Atomic Force Microscope Results Sample 12

Sample 13:

Etchant Concentration (%HCl v/v)	=	12%
Current (mA)	=	65 mA
Temperature (°C)	=	25°C
Time taken for 10 micron depth	=	32 sec
Kerf Angle measured from optical microscope	=	55°
Surface Roughness (S_a)	=	236 nm



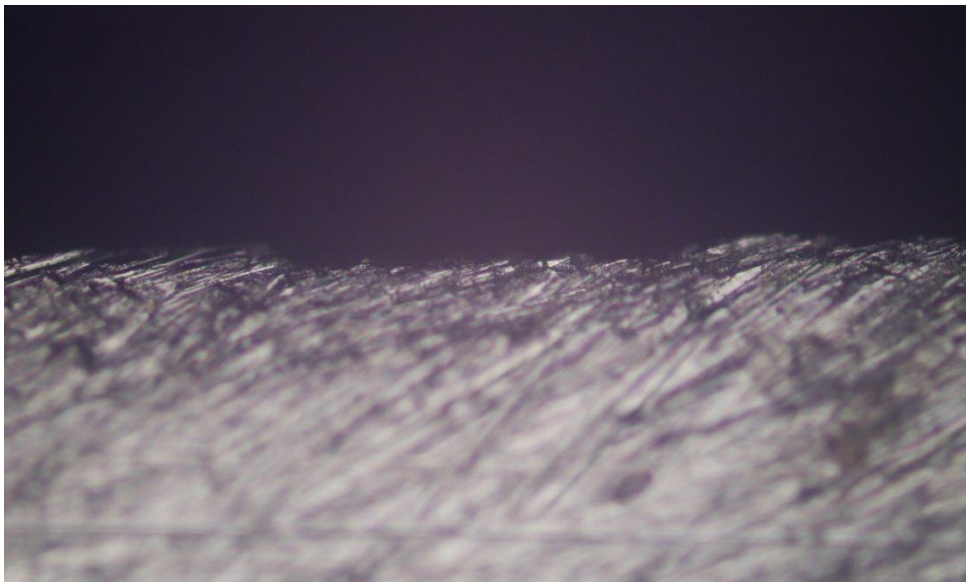
Optical Microscope Image Sample 13 (x200)



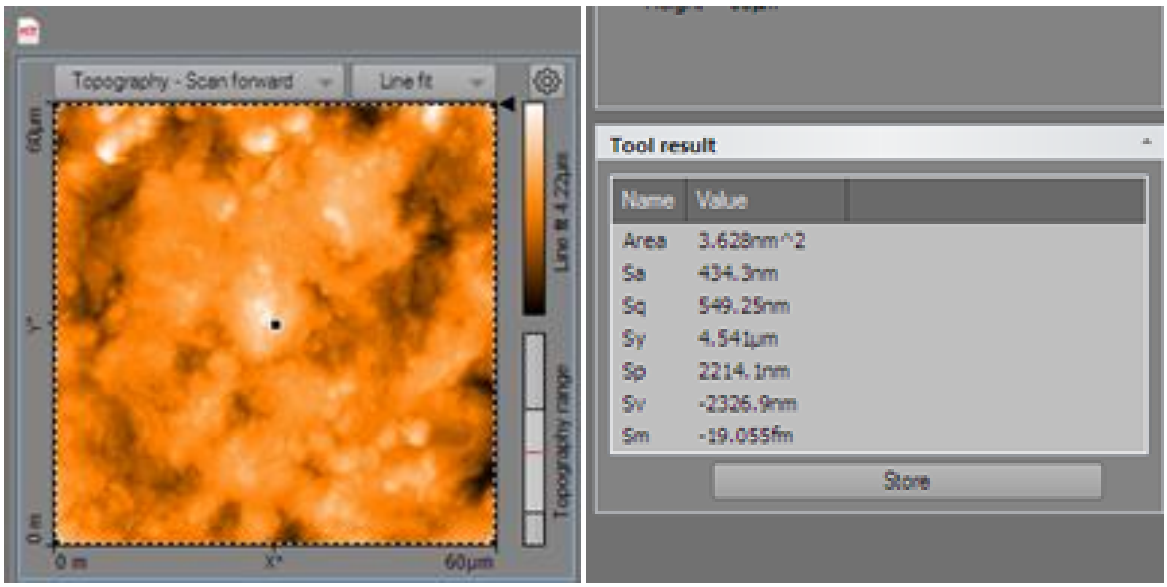
Atomic Force Microscope Results Sample 13

Sample 14:

Etchant Concentration (%HCl v/v)	=	12%
Current (mA)	=	60 mA
Temperature (°C)	=	35°C
Time taken for 10 micron depth	=	35 sec
Kerf Angle measured from optical microscope	=	56°
Surface Roughness (S_a)	=	434 nm



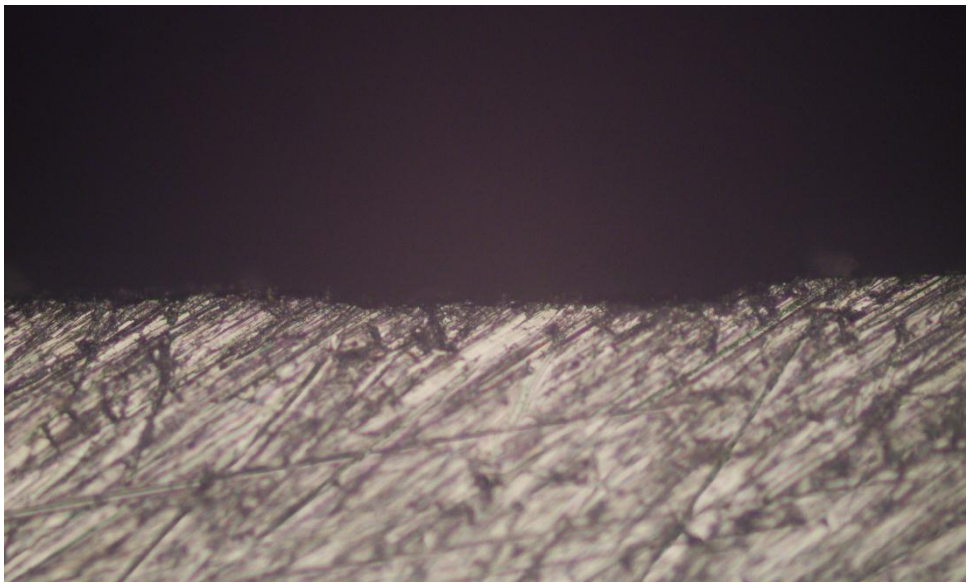
Optical Microscope Image Sample 14 (x200)



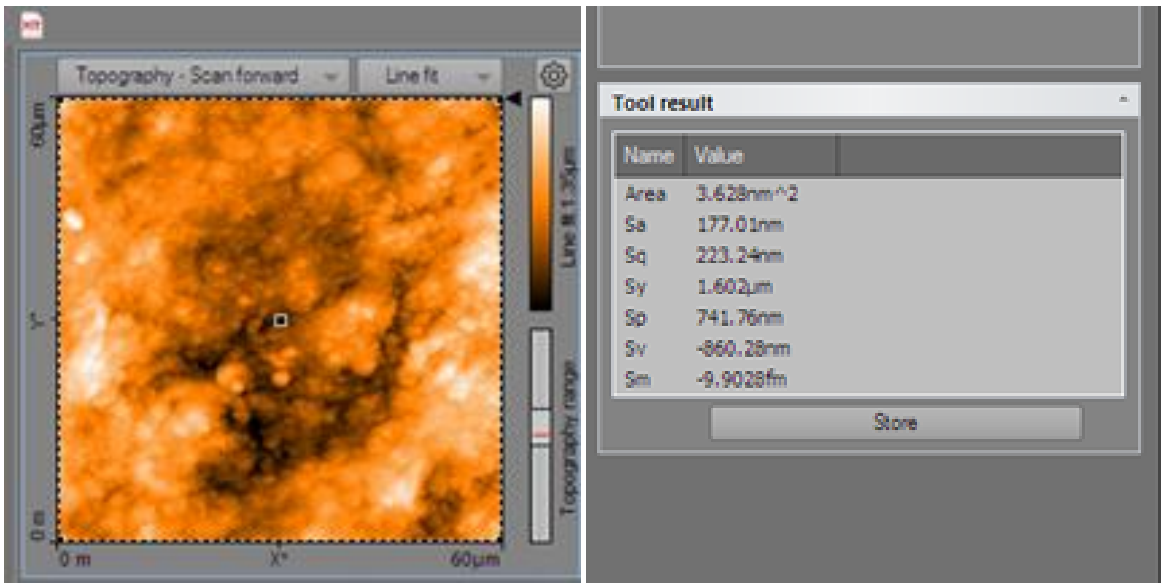
Atomic Force Microscope Results Sample 14

Sample 15:

Etchant Concentration (%HCl v/v)	=	12%
Current (mA)	=	55 mA
Temperature (°C)	=	45°C
Time taken for 10 micron depth	=	40 sec
Kerf Angle measured from optical microscope	=	65°
Surface Roughness (S_a)	=	177 nm



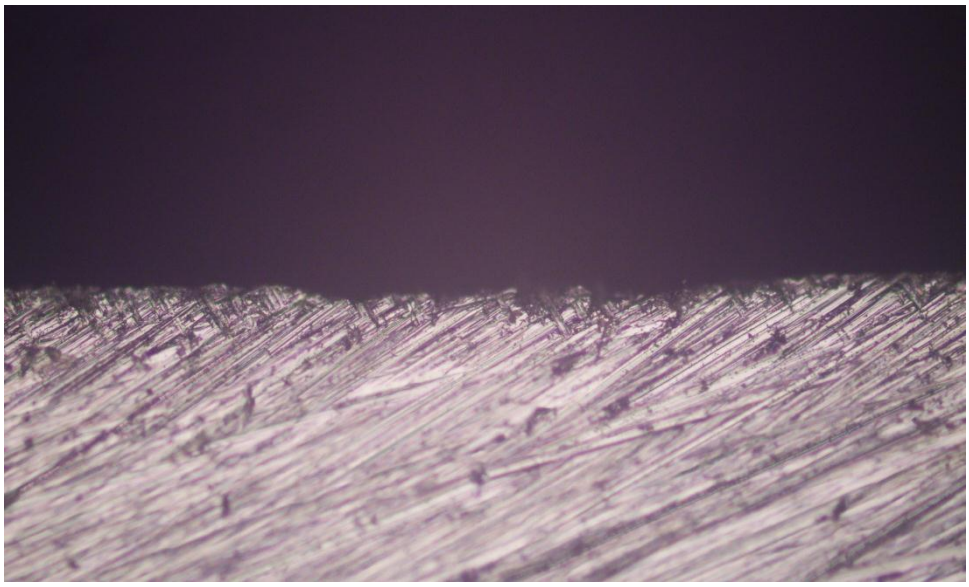
Optical Microscope Image Sample 15 (x200)



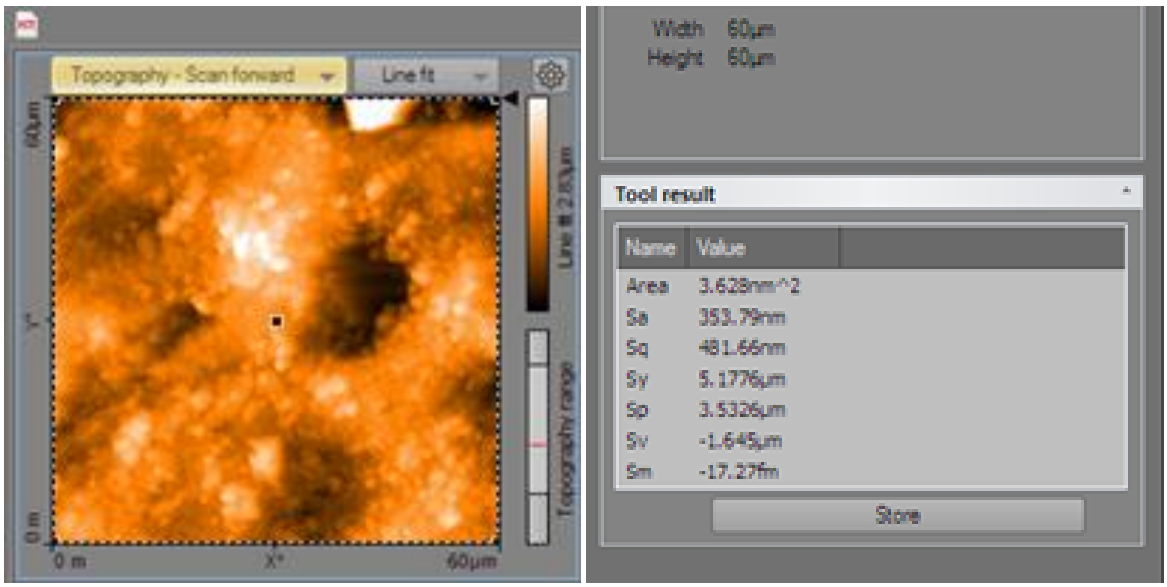
Atomic Force Microscope Results Sample 15

Sample 16:

Etchant Concentration (%HCl v/v)	=	12%
Current (mA)	=	50 mA
Temperature (°C)	=	55°C
Time taken for 10 micron depth	=	50 sec
Kerf Angle measured from optical microscope	=	76°
Surface Roughness (S_a)	=	354 nm



Optical Microscope Image Sample 16 (x200)



Atomic Force Microscope Results Sample 16

3.2 Analysis on Minitab:

3.2.1 ANOVA:

Time Required for 10 um Depth:

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Etch. Conc	3	291.19	47.74%	291.19	97.062	9.98	0.010
Current	3	239.19	39.22%	239.19	79.729	8.19	0.015
Temp	3	21.19	3.47%	21.19	7.062	0.73	0.573
Error	6	58.37	9.57%	58.37	9.729		
Total	15	609.94	100.00%				

Surface Roughness:

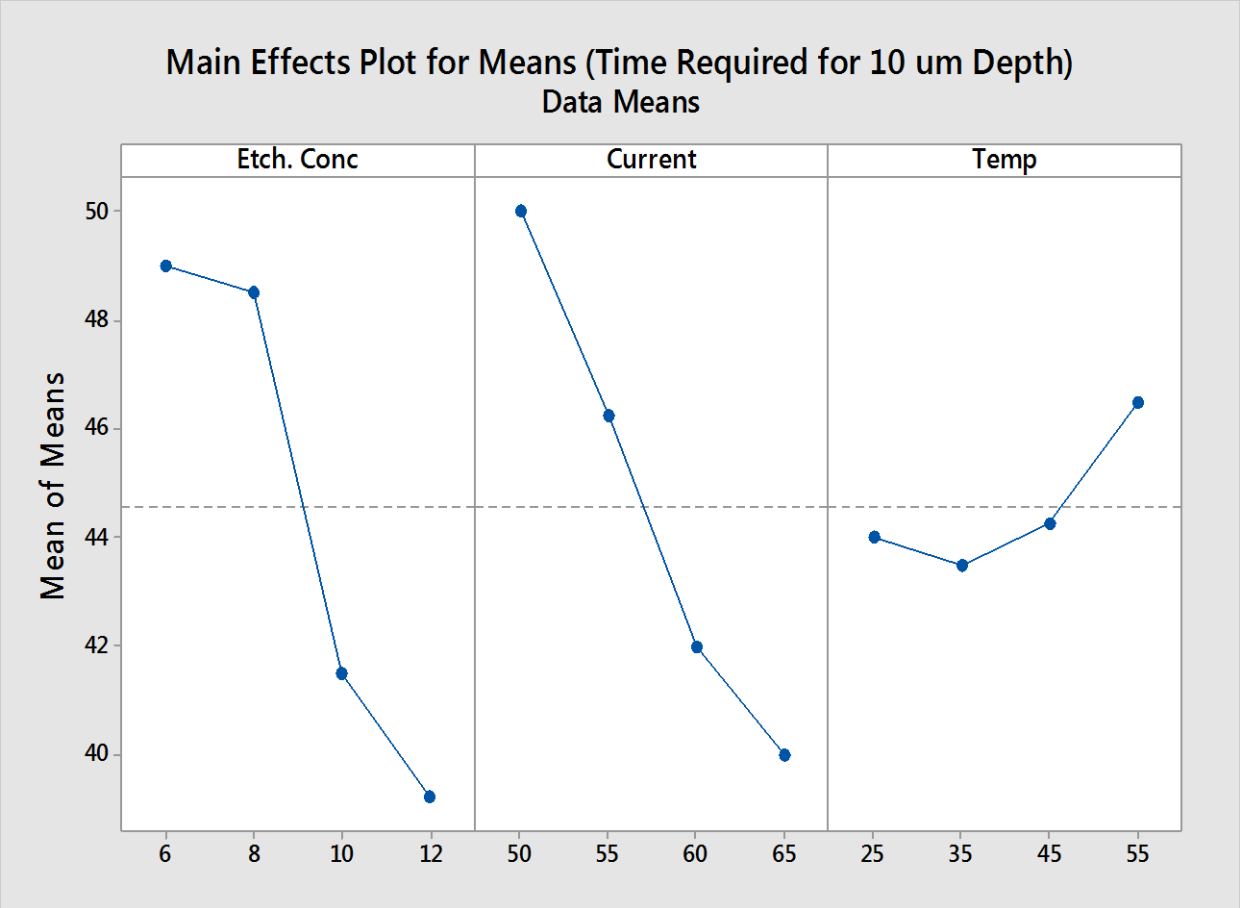
Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Etch. Conc	3	38720	14.09%	38720	12907	0.60	0.637
Current	3	90219	32.82%	90219	30073	1.40	0.330
Temp	3	17354	6.31%	17354	5785	0.27	0.845
Error	6	12859	46.78%	128599	21433		
Total	15	274891	100.00%				

Kerf Angle:

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Etch. Conc	3	519.19	41.00%	519.19	173.06	6.81	0.023
Current	3	532.19	42.02%	532.19	177.40	6.99	0.022
Temp	3	62.69	4.95%	62.69	20.90	0.82	0.527
Error	6	152.37	12.03%	152.37	25.40		
Total	15	1266.44	100.00%				

3.2.2 Main Effect Plots:

Time Required for 10 um Depth:



Main effect plot shows machining time required for 10 micron depth decrease as etchant concentration increases.

Main effect plot shows machining time required for 10 micron depth decrease as current supplied increases.

Main effect plot shows machining time required for 10 micron depth increases as solution temperature increases.

The results for which time of etch of these samples was most optimum were performed subsequently. The factors which yielded lowest time were:

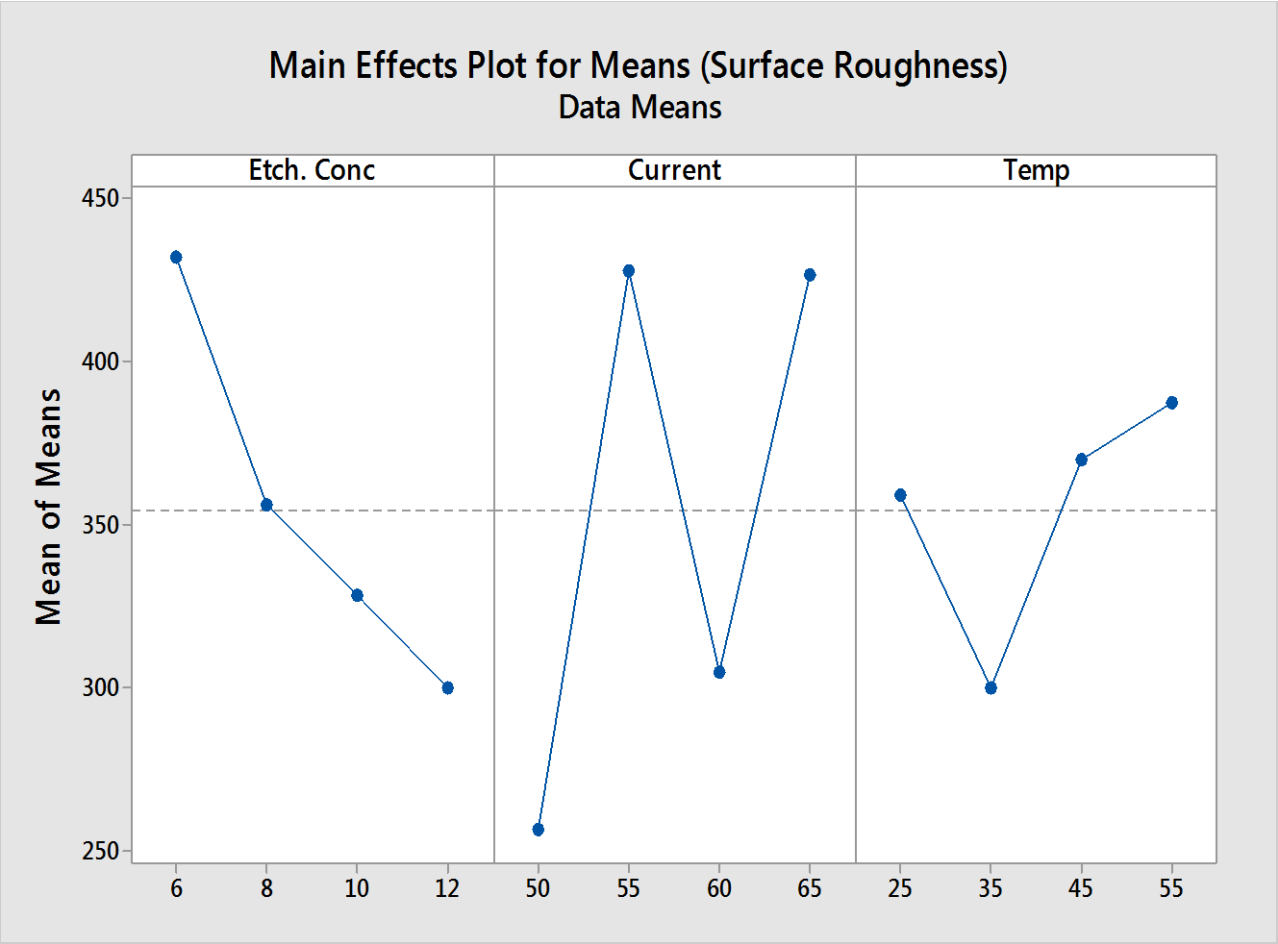
Electrolyte Concentration: 12% HCl v/v

Current: 65 mA

Temperature: 35º C

Time for 10 um depth: 36 sec

Surface Roughness:



Main effect plot shows that surface roughness decreases as etchant concentration increases.

Main effect plot shows that surface roughness has no identifiable effect as current increases.

Main effect plot shows that surface roughness has no identifiable effect as temperature increases.

The results for which surface roughness of these samples was most optimum were performed subsequently. The factors which yielded most optimum surface roughness were:

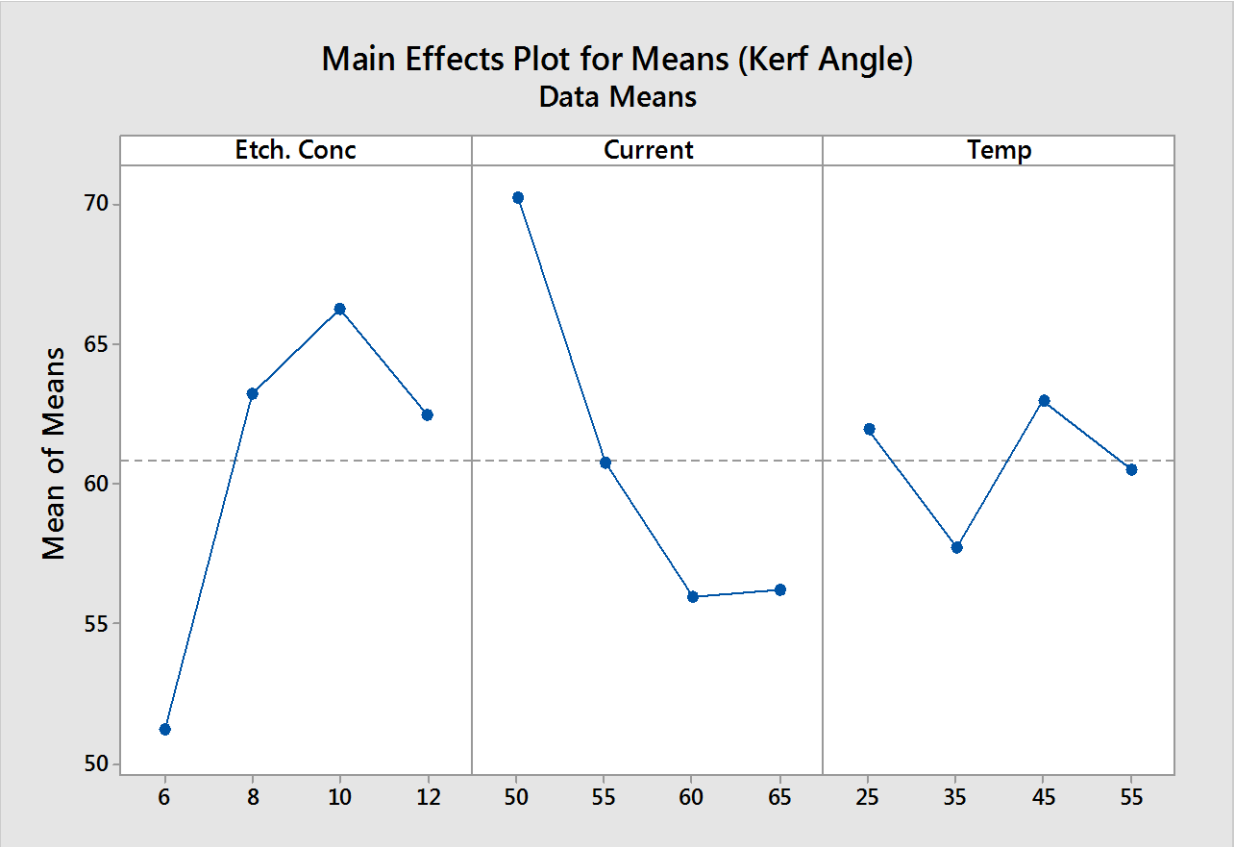
Electrolyte Concentration: 12% HCl v/v

Current: 50 mA

Temperature: 35° C

Surface roughness: 319/354/357 nm

Kerf Angle:



Main effect plot shows that Kerf Angle initially increases as etchant concentration increases.

Main effect plot shows that Kerf Angle decreases as current supplied increases.

Main effect plot shows that Kerf Angle has no identifiable effect as temperature increases.

The results for which kerf angle of these samples was most optimum were performed subsequently. The factors which yielded the most optimum kerf angle were:

Electrolyte Concentration: 10% HCl v/v

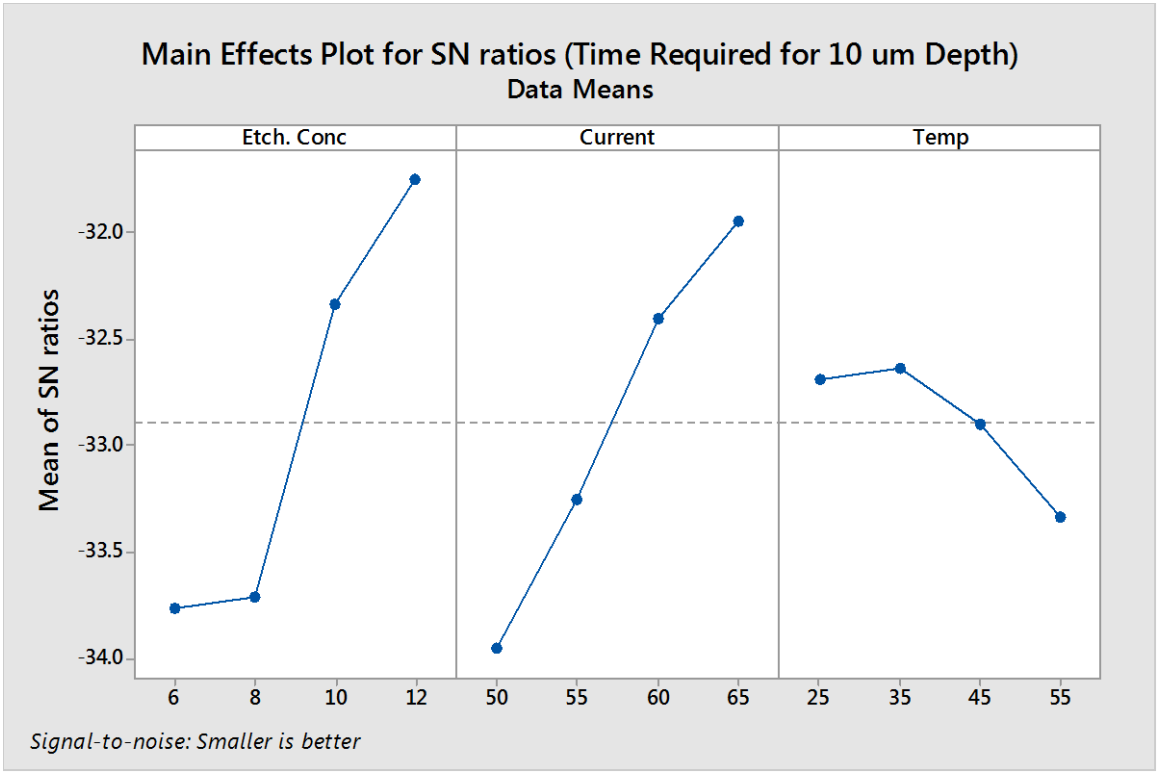
Current: 50 mA

Temperature: 45º C

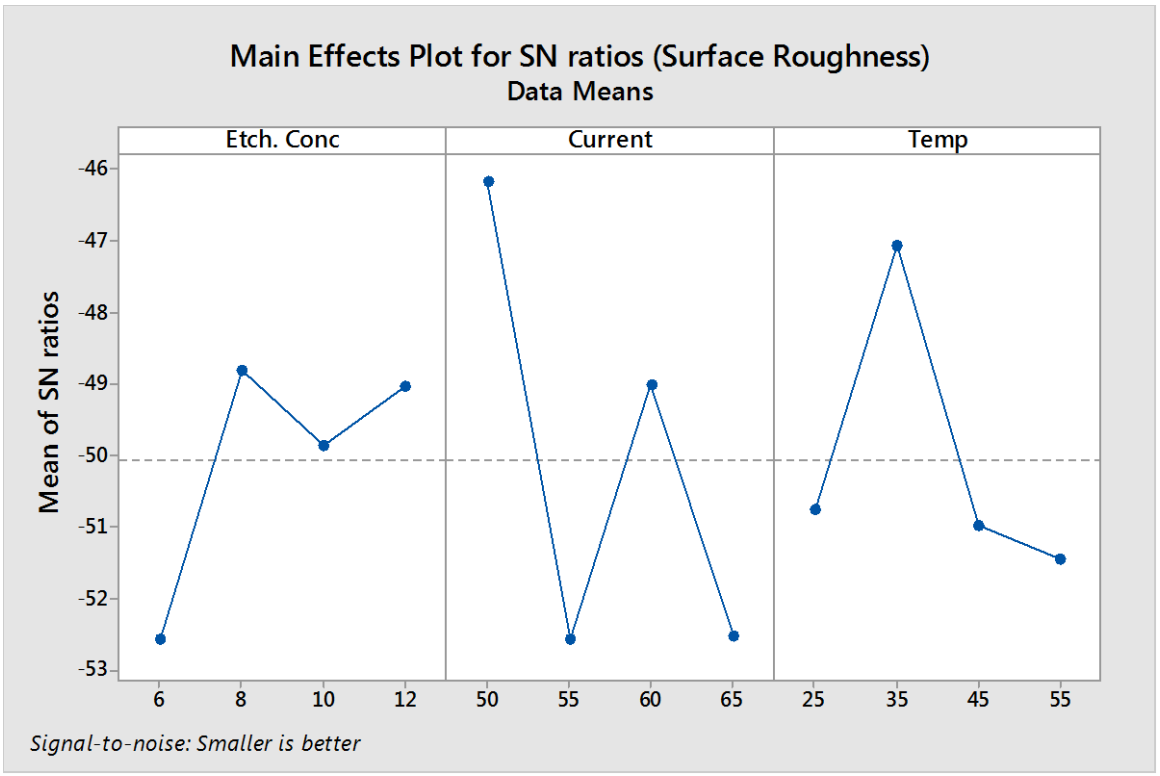
Surface roughness: 76 deg

3.2.3 S/N Ratios:

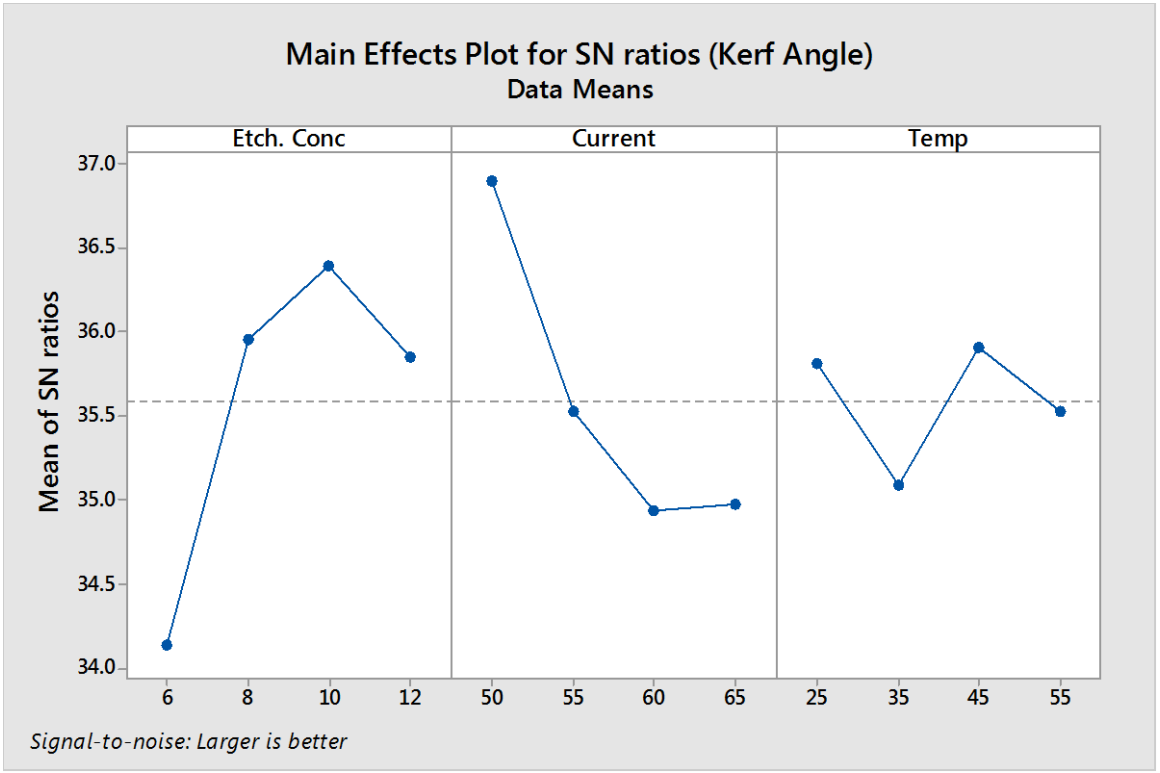
Time Required for 10 um Depth:



Surface Roughness:



Kerf Angle:


Main Effects Plot for SN ratios (Kerf Angle)
Data Means
Etch. Conc
Current
Temp
Mean of SN ratios
37.0
36.5
36.0
35.5
35.0
34.5
34.0
6
8
10
12
50
55
60
65
25
35
45
55
Signal-to-noise: Larger is better

3.2.4 Percent Contribution:

Time Required for 10 um Depth:

Sr. No.	Source	Percent Contribution
1	**Etch. Conc**	47.74%
2	**Current**	39.22%
3	**Temp**	3.47%
4	**Error**	9.57%
5	**Total**	100.00%

Surface Roughness:

Sr. No.	Source	Percent Contribution
1	**Etch. Conc**	14.09%
2	**Current**	32.82%
3	**Temp**	6.31%
4	**Error**	46.78%
5	**Total**	100.00%

Kerf Angle:

Sr. No.	Source	Percent Contribution
1	**Etch. Conc**	41.00%
2	**Current**	42.02%
3	**Temp**	4.95%
4	**Error**	12.03%
5	**Total**	100.00%

Chapter - 4: Conclusion

Machining Time:

- Machining time required for 10 micron depth decreases as etchant concentration increases.
- Machining time required for 10 micron depth decreases as current supplied increases.
- Machining time required for 10 micron depth increases as solution temperature increases

Surface Roughness:

- Surface roughness decreases as etchant concentration increases.
- Surface roughness has no identifiable effect as temperature increases.
- Surface roughness has no identifiable effect as current increases.

Kerf Angle:

- Kerf Angle has no identifiable effect as temperature increases.
- Kerf Angle decreases as current supplied increases.
- Kerf Angle initially increases as etchant concentration increases.

4.1 Future Recommendations

New responses and factors can be added in the process like inter electrode gap and new etchants can be tried for improved surface roughness and kerf angle.

References

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[4] K. P. Rajurkar, B. Wei, J. Kozak, Lincoln, & J. A. McGeough "Modeling and Monitoring lnter electrode Gap in Pulse Electrochemical Machining."

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