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Enhancing Surface Finish Of Fused Deposition Modeling Parts Through Targeted Chemicals And Design Of Experiments

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Abstract

Fused Deposition Modeling (FDM) is one of the most popular rapid prototyping (RP) technologies due to its low operational cost, high fabrication speed, and range of applications served. However, FDM fabricated parts generally have poor surface finish quality which have limited their utilization in end-use applications. To enhance surface quality of FDM materials, several researchers have regulated key process parameters using the FDM material, Acrylonitrile Butadiene Styrene (ABS), with varying results. The main goal of this research is to investigate the effects of a post-fabrication chemical treatment process on the surface roughness for FDM parts of the FDM material ULTEM. ULTEM is selected for this study due to its potential utilization in a wide range of applications requiring high tensile strength, flexural stress, and high strength to weight ratio. The key challenge of this research is to overcome the fact that ULTEM is a chemical resistant material and thus it is harder to improve the surface finish by using post-chemical treatments used by previous researchers. To overcome this challenge, a detailed design of experiments (DOE) study is proposed where ULTEM samples will be exposed to different chemicals while varying several parameters such as levels of chemical concentration, temperature of chemical solutions sand time of exposure to chemicals. Analysis of Variance (ANOVA) technique will be used to identify the significant factors affecting the surface finish of FDM built parts. In summary, this research will lead to improvements in surface finish of the FDM material ULTEM with a simple and inexpensive chemical treatment process.

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Chapter 1: Introduction

Rapid Prototyping (RP) technologies build prototypes of actual models from different materials with desired properties. Stratasys introduced the Fused Deposition Modeling (FDM), which is a RP process that can build prototypes out of different thermoplastics, in 1990 [1]. Parts built by other RP processes like Stereo Lithography Apparatus (SLA) are much more accurate than those built by FDM [2]. However, FDM is widely used in Industry due to its ability to fabricate high-strength parts, low cost operation, and ease of fabrication without extensive post-fabrication cleaning. Using FDM technology, 3D printers can build parts layer-by-layer by heating and extruding a variety of thermoplastic filaments with application specific properties, as shown in Figure 1.

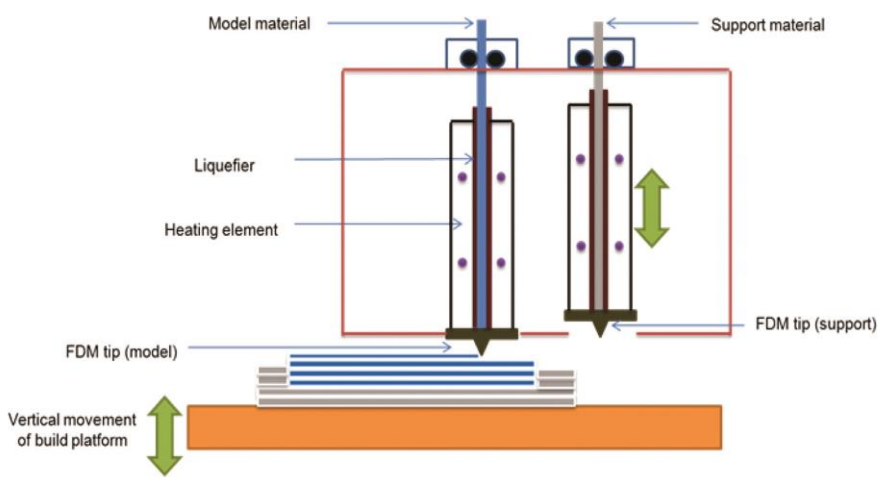


Figure 1.1: Schematic diagram of fused deposition modeling [7].

FDM is generally used for building products with complex geometry and functional parts, prototypes, low volume production pieces, manufacturing aids and jigs and fixtures. The FDM process starts with the software that processes the part built to STL (Stereo Lithography file format) slicing and orienting the model for printing. Support material can be generated in the design itself. The machine can discharge two materials one is support material and the other is the

main material. The part is made by the extrusion of small flattened strings of molten materials to form layers of the part, as materials converted to solid state immediately after the extrusion of material from nozzle. Material transmits from solid state to liquid state because the nozzle is heated to a temperature where the material transforms itself to a liquid state and quickly after the material is extruded in desired shape it cools down to give the designed product. After the product is obtained support material can be removed by detaching it or immersing it in water if it is soluble to reach the final product.

A key drawback with the FDM process is surface roughness (staircase effect) caused due to the layer-by-layer build process and forming larger layer thickness [3]. Many researchers have introduced different methods to reduce the surface roughness of the FDM parts, using Acrylonitrile Butadiene Styrene (ABS) thermoplastic. Some of the most effective methods for improving surface roughness were; optimization of build orientation, in this research the model was built by varying build orientation, layer thickness and keeping other parameters constant of FDM process using experimental design technique [4]. Another novel method for reducing surface roughness was the prediction of dimensional accuracy based on artificial neural network, which helped optimize the parameters within the 3D printer to achieve the best surface finish [5]. Bual and Kumar (2014) proposed a slicing strategy where layer thickness of 177.8 µm and part orientation of 70° significantly improved the surface roughness achieving a good surface finish [6]. Galantucci *et al.* (2009) proposed a useful solution for improving surface finish using a post-chemical treatment method [3]. Di-Methyl ketone (Acetone) with 90% concentrated solution and 10% water was used for treating FDM parts built using ABS thermoplastic by immersing them in the solution for 5 minutes resulting in a very good surface finish [2].

FDM material ULTEM has recently become one of the most emerging thermoplastic due to its desirable mechanical properties like high tensile strain, flexural stress, tensile elongation and it is chemically retardant material which makes it more interesting [7]. ULTEM 9085 is flame-

retardant high performance thermoplastic and it is ideal for transportation industry applications due to its high strength–to-weight ratio and its flame, smoke and toxicity (FST) rating. However, due to its chemically resistant properties, ULTEM presents a challenge to improve surface finish using previously successful post-chemical treatment process. As a result, a detailed statistical study needs to be conducted using DOE to optimize the process in terms of the solution concentration, solution temperature, initial roughness, immersion time and the interaction of these parameters. For ULTEM, Stratasys has recommended the chemicals, Methyl Ethyl Ketone (MEK), Di-Methyl Ketone and Strong Hydrofluoric Acid for experimental studies involving surface roughness improvement [7]. MEK is an organic compound, produced industrially on a large scale, soluble in water, and is commonly used as an industrial solvent [8]. Strong Hydrofluoric Acid is used as a pickling agent to remove oxides and other impurities from stainless and carbon steels because of its limited ability to dissolve steel and is used in the semiconductor industry as a major component, which is used to clean silicon wafers [8]. Strong Hydrofluoric Acid has not been used by us in performing the experiments because it has a great amount of terms and conditions in storing the chemicals as well as in using the solution there were many regulations to be followed improper use of solution might lead to serious health issues. Thus, MEK and Di-Methyl Ketone were selected which have the potential to improve the surface roughness of a chemically resistant material such as ULTEM and thus will be utilized for this research.

1.1 OBJECTIVE

Now a days, there is an evidence of enhancing the surface roughness of the 3D printed parts from the ABS and few other thermoplastic material, but there is no evidence of improving the surface roughness of the 3-D printed parts from ULTEM material via chemical treatment method. This study seeks to develop the most economical way to approach the problem. This will cover Design of Experiments for analyzing the chemical post processing treatment method to identify the main controlling factors side effects of the process parameter setting and disturbances

of the process for ULTEM thermoplastics. A more specific scientific objective of this research is to develop the optimum condition with different chemicals for improving surface roughness of ULTEM thermoplastics.

1.2 CONTRIBUTION

This thesis covers the data preparation, solution preparation, performance of experiment, selection of significant factors and chosen methodology to conduct this research. Moreover this thesis also includes the application of the methodology to the 3-D world. This thesis can also be served as professional guidance to the 3-D printing industry in order to address the surface roughness problems most economically. Benefits of proposed method can be significant improvement in surface roughness an accurate identification of significant factors and drastically reduction in cost for reducing surface finish of final product as a consequence, increase of the profit is feasible.

1.3 MOTIVATION

Surface finish has become one of the primary defects in 3D printing parts thus leading in investing more to reduce this defect moreover it also affects the mechanical properties of the part. There is no evidence of a similar approach using ULTEM to address the current issue. The main motivation of this research is to reduce the surface finish without decreasing the mechanical properties of printed parts and the monetary cost associated with the problem as well. This research seeks to address the actual target that has been a large problem during the past years. It is important to clarify that the 3-D printing is becoming more sophisticated and complex in day to day life. While printing the product materials are printed layer by layer as a consequence it causes staircase effect (the angle between vertical axis and surface tangents) which leads to surface roughness. Surface roughness is also caused when the support material is removed from the main material leaving some burrs on the surface of the main material. Focusing on addressing this huge problem using chemicals for the post treatment of parts to reduce the surface roughness.

Additionally this thesis would help in reducing the surface finish of new FDM materials. Finally, the contributions in the study could be analyzed and the methodology may be added.

Chapter 2: Problem Statement

Generally, one of the serious issues in 3D printing which needs to be addressed for increasing its applicability is surface roughness of the final product. Parts built via 3D printers will always have staircase effect on the surface of parts because of the deposition of molten materials in layer patterns on top of each other and results in increased surface roughness and poor mechanical properties. Poor surface roughness effects friction, wear, pressure drop and boundary layer etc. which affects the performance of the product. Additionally, there are burr marks on the surface of the main material after the support material is removed, which also leads to poor surface finish.

As mentioned before, the FDM material ULTEM 9085 has few exceptional properties like high strength–to-weight ratio and its flame, smoke and toxicity (FST) rating which makes it an excellent choice for the commercial transportation industry-especially aerospace, marine and ground vehicles [7]. However, ULTEM 9085 is chemical retardant material, and thus, reducing the surface roughness of ULTEM through post chemical treatment is a challenging research topic and is the main objective of the research. Currently, a chemical treatment method has not been thoroughly analyzed for ULTEM considering different types of chemical concentrations, temperature of chemicals, and time of exposure to FDM parts to recommend optimum parameter combinations for obtaining best surface finish. In this research, well-designed experiments (DOE) will be carried out for interpreting the main controlling factors for chemical treatment of ULTEM. Additionally, Analysis of Variance (ANOVA) technique will also be used to find out the significant factors affecting the surface finish.

Chapter 3: Literature Review

3.1 FDM Overview

Fused Deposition Modelling is one of the leading rapid prototyping technologies in the world with the stereo lithography. FDM was built in 1989 and marketed in 1990 by Stratasys Inc., In FDM a plastic filament is unwound from a coil and is fed into a liquefier where it is melted. A plunger extrude the material through nozzle which is the solid portion of the incoming filament.

On the mechanical stage, a nozzle is being mounted which can be moved in XY plane. Nozzle deposits a thin bead of extruded plastic when it is moved on top of the table in a pre-specified configuration to form the road. In a rastering configuration, stocking of roads side-by-side produces each layer. The polymer hardens immediately after being extruded through the nozzle and the new layer is bonded to the lower layer. As soon as first layer is built, the platform is lowered in z direction in order to make the station ready for the next layer.

The chamber consists of entire system in which part is built. Chambers provide the temperature controlled environment with temperatures just below the melting point of the polymer which in a way help to bind layers together more effectively.

There are many materials which are commercially available for this process like ABS and ULTEM. ABS offers good strength, and more recently ULTEM 9085 and ULTEM 1010 materials have been introduced which extend the capabilities of the method further in terms of strength and temperature range. Support structures are also built using the support material for the overhanging parts that are there in the main product and removed later by either breaking them away from the object, or if it is a water soluble part which can be simply washed away using water.

This process is eco-friendly process and does not produce too much noise. FDM is too fast for the products which have tall, thin form-factors or small parts which consume few cubic inches. Though, it can consume a lot amount of time for parts with wide cross sections.

3.2 FDM Definition

Fused Deposition Modeling is one of the frequently used additive manufacturing process to produce the prototypes and end product parts. Components and assemblies are manufactured from thermoplastic material via 3 D Computer Aided Design (CAD) in only a few working steps. Software automatically slices the data, calculate the support material required and creates the toolpath. The material of the deposition layer bonds with the layer beneath it and solidifies due to the thermal fusion thus, resulting in a permanent bonding between two layers that are formed therefore, creating the desired product.

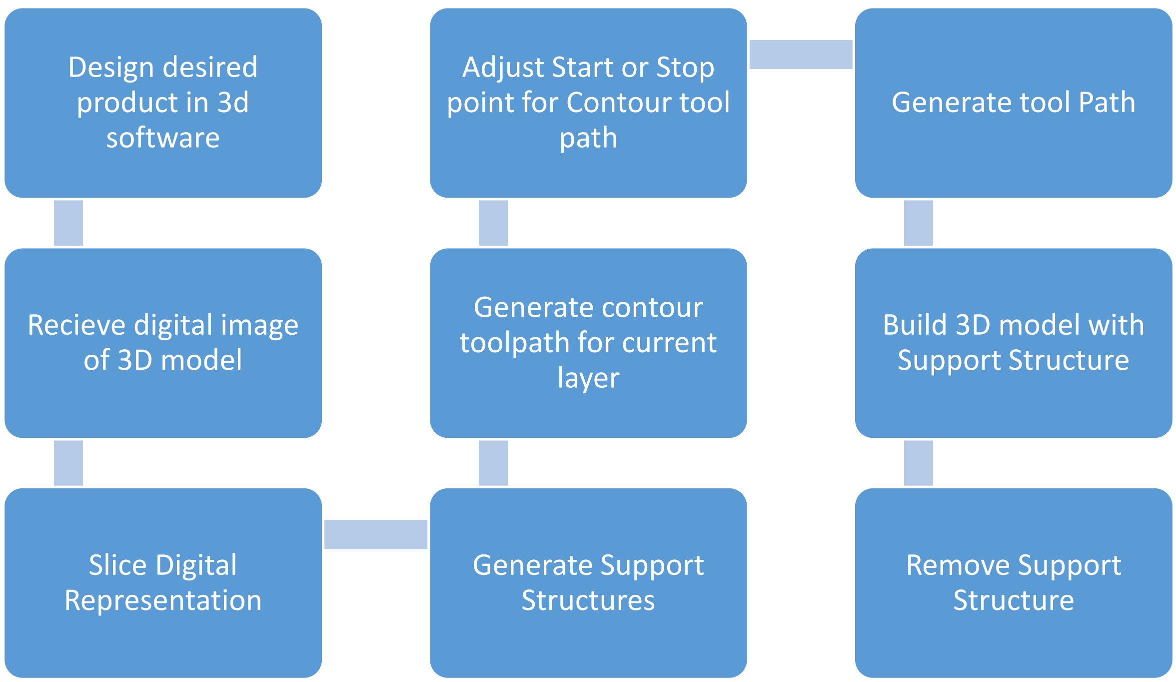


Figure 3.1: Flowchart of fused deposition modelling.

3.3 Material

ULTEM is one of the thermoplastic which has two types of range; they are ULTEM1010 and ULTEM 9085. The ULTEM resin family of amorphous thermoplastic polyetherimide (PEI) resins offer outstanding elevated temperature, high strength and stiffness and broad chemical resistance. ULTEM 9085 resin is a flame retardant, high-performance thermoplastic for digital

manufacturing and rapid prototyping. It is ideal for the transportation industry due its high strength to weight ratio and it has good Flame, smoke and toxicity (FST) rating. It is available in transparent, opaque and glass filled colors. They are generally used in where higher heat, chemical and elasticity is required. ULTEM 9085 is one of the 3-D printed thermoplastic which balances both mechanical property and process ability.

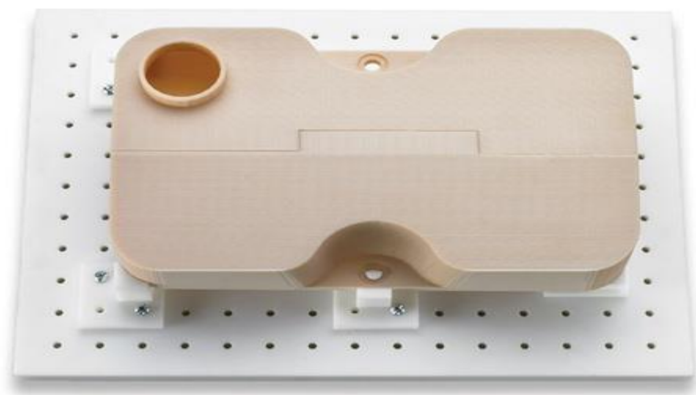


Figure 3.2: A gas tank prototype with ULTEM 9085 material [7].

3.4 SURFACE ROUGHNESS

Surface roughness is a factor for measuring the surface texture because roughness plays an important role in deciding how an object will interact with the environment. High roughness value is mostly undesirable, because rough surfaces generally wear more quickly than smooth surfaces. Poor surface roughness leads to cracks and corrosion. Improving the surface roughness will lead to the increasing in manufacturing cost. Major issue with the improving in surface roughness is decrease the surface roughness without increasing the manufacturing cost. The underline statement of this thesis is improving the surface roughness without increasing the manufacturing cost for the 3D printed parts.

3.5 CHEMICALS

FDM rapid prototyping process is common in the market for many reasons, such as the fact that various types of raw materials can be used, cheaper process and less safety related problems are there. The only major issue with the FDM parts are surface roughness due to its staircase effect. To improve the surface finish without increasing the manufacturing cost a lot chemical treatment has been proposed by L.M.Galantucci et al [2]. The chemicals which are chosen to improve the surface roughness are Di-Methyl ketone and Methyl Ethyl Ketone after consulting from the Stratasys.

Di-Methyl ketone in generally is known as acetone, it is an organic compound that has the chemical formula as $(CH_3)_2CO$. It is colorless, volatile and flammable liquid it is one of the simplest type of ketone. Acetone is miscible with water and serve as an important solvent. It is basically used in laboratory for the cleaning purposes. It is an important ingredient in nail polish remover and is also used in in paint thinner.

Methyl Ethyl Ketone is another chemical which is commonly known as Butanone, it is also an organic compound which has the chemical formula as CH_3C (O) CH_2CH_3. Butanone is a colorless liquid ketone it also has sharp and sweet odor. It is produced in industry on large scale and is also present in trace amounts in environment. It is soluble in water and is commonly used as industrial solvent.

3.6 DESIGN OF EXPERIMENTS

Design of Experiments (DOE) was firstly introduced in the beginning of 1900s. It was developed in England by Ronald A. Fisher. He led to the first type of its applications in the field of agriculture. It was in 1980 that this methodology was set up and run by few of the specialists within an organization. The Design of Experiments Process is presented in Figure below in a form of a flowchart. The objective in many cases may be to develop a robust process, that is, a process affected minimally by external sources of variability [11]. Individual and interactive effects of

many factors that affect the output can be found by applying this methodology, since it provides a full insight of interaction between design elements. DOE come across two types of process variables (factors): qualitative and quantitative factors [11]. Quantitative factors are set up in a range of settings which can be measured and controlled during the experiment, such as speed, temperature, etc. Qualitative factors are discrete in nature, such as type of raw material, type of supplier, type of catalyst, etc. Three basic principles which need to be followed for an experimental design to reduce or even remove experimental bias: randomization, replication, and blocking. Randomization describes a process where the outcomes do not follow a deterministic pattern. Replication is the number of experimental trials to be run for a process. Blocking eliminates the effect of variation due to noise factors, so it improves the efficiency of experimental design.

3.7 Alternative Method for Surface Improvement

As the different materials and processes kept increasing the popularity of additive manufacturing kept on advancing gradually. Additive Manufacturing is from building the prototype to manufacturing with only one aspect in mind aesthetic quality and functionality. In maintaining of the purpose the additive manufacturing is lacking in improving the surface finish of the final product. Finishing of the prototype can be done in many ways depending on the time, quality and the expense a person is ready to invest in the final product. The most easy and readily available technique is to sand the product either by tools or by hand. This technique is only available for products with the limitation of the size and feature. If product has too many features, small extrusions, or deep cavities sanding of these products become too time consuming, costly and add to labor cost of the product. Before sanding a product parts may have a filler or primer applied it is done to the part before painting because it gives the product a smooth surface finish. Applying a filler or primer adds the cost of buying a product as well as it adds the time of the labor to coat the product. This increase the lead time and the expense of the product.

3.8 TAGUCHI METHOD

Taguchi methods have been widely used in Japanese products for improving the quality since 1960. Many companies found out that the old methods for ensuring quality were not as effective as the Japanese methods. Basically, the old methods relied on just inspecting products and rejecting those products that did not fall within a certain acceptance range. An effort to improve product quality and design robustness, the United States and Europe adopted this approach. Robust design is an "engineering methodology for improving productivity during research and development so that high-quality products can be produced quickly and at low cost" [11]. This methodology is focused on improving the quality of a product by analyzing the variation without eliminating the causes. This approach was based on conventional statistical tools together with some guidelines in order to design experiments and analyzing the results of these experiments. Taguchi's approach to quality control applies to the entire process of developing and manufacturing a product—from the initial concept, through design and engineering, to manufacturing and production [12]. Quality Loss Function was defined in order to measure quality. It is a continuous function that is defined in terms of the deviation of a design parameter from an ideal or target value.

Quality loss function can be minimized by monitoring the process variables during production and adjust the process in order to reduce manufacturing errors so that response parameters fall within the specified tolerances. According to Taguchi, quality can be achieved with the application of a three-stage process, the stages being system design, parameter design, and tolerance design. Two types of factors that affect a product or a process are control factors and noise factors. Control factors are controlled easily, such as material choice, cycle time, or temperature. Noise factors are difficult or impossible to control. Outer noise, inner noise, and between product noise are three types of noise factors. Analysis of the signal-to-noise (SN) is the preferred parameter setting where factor levels that maximize the appropriate SN ratio are optimal.

It is established in order to minimize the sum of the manufacturing and lifetime costs of the product or process. Orthogonal Arrays (OAs) are used in the Taguchi method. The most used OAs are L4, L9, L12, L18, and L27. Factors and their corresponding levels are indicated in the columns in the OA. Each row represents an experimental run that is performed at the given factor settings. The bulk of the effort to plan a robust design experiment is to select properly the number of levels and quantities.

	Factors		
Run	A	B	C
1	1	1	1
2	1	2	2
3	2	1	2
4	2	2	1

(a) L_4 (2^3) array

	Factors						
Run	A	B	C	D	E	F	G
1	1	1	1	1	1	1	1
2	1	1	1	2	2	2	2
3	1	2	2	1	1	2	2
4	1	2	2	2	2	1	1
5	2	1	2	1	2	1	2
6	2	1	2	2	1	2	1
7	2	2	1	1	2	2	1
8	2	2	1	2	1	1	2

(b) L_8 (2^7) array

	Factors			
Run	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

(c) L_9 (3^4) array

Figure 3.4: Commonly used orthogonal arrays [10].

3.9 Comparison and Critiques between Fractional Factorial Design and Taguchi Method

The Taguchi method has generated discussion controversy about the performance of the methodology and its statistical foundations for data analysis. A point to note about this methodology is that it provides information about the interactions between the noise factors and the controllable factors by the use of the crossed array design. A major problem of the Taguchi approach is that due to the use of an external array in the experimental design for the analysis of the noise factors, it can lead to a very large experiment, and sometimes, the size of the inner array sacrifices the resolution of the experiment. According to Montgomery's point of view, the signal to noise ratios are problematic because they may result in confounding the location and dispersion effects and they often do not produce the desires result of finding a solution to the robust parameter design problem that minimizes the transmitted variability of the noise factors to the controllable

ones. The factorial designs test every possible factor-level combination; a fractional factorial design involves only a specific subset or fraction of these combinations. It is designed to have fewer runs. This methodology is possible because of the sparsity-of-effects principle that states that for most systems, only main effects and lower-order interactions have a significant effect, whereas higher-order interactions are relatively insignificant. The factor confounding is a disadvantage of this approach. This is due of the reduced number of runs, and refers to main effects or interactions in the design that are combined or correlated with other factor effects or interactions. The comparison between fractional factorial design and Taguchi method is presented in Table 3.1.

Table 3.1: Comparison between fractional factorial design and taguchi method.

Characteristic	**Fractional Factorial Design**	**Taguchi Method**
Process Knowledge	Assume no understanding of the fundamental mechanisms governing the process	Assume a certain understanding of the process and the interactions that are likely to exist between inputs.
Combinations of Inputs Tested	Test all combinations of input levels, or some symmetrical subset	Test a small fraction of all possible combinations, but in a manner that allow calculating the effects of all inputs on the output.
Noise Factors	Ignores noise factors	Make use of Noise Factors to test robustness of the system and find optimal inputs.
Understanding of Variability	Ignores variability in the process; it assumes a deterministic nature to the system, and finds combinations of input variables that maximize or minimize output, as the case may be.	Assume a stochastic nature to the system; it looks at both the levels of output and the variability of the output; it lets to select levels of input variables to maximize or minimize output or to minimize variability of output
Confirming Experiment	Require no confirming experiment, since all combinations of inputs were tested	Recommends a confirming experiment

3.10 FACTORS IN IMPROVING SURFACE ROUGHNESS

In case for improving the surface perspective, roughness has been identified as a very frequent defect. In order to address this problem, the solution has been varied in with four different factors. For the objective of this research, one or multiple of the decided factor might help to give the desired output. These factors were decided on the basis of the preliminary experiments which were carried out to see that the factors improved the product. Table 3.2 shows the four factors decided for improvement of surface roughness and the explanation of each one.

Table 3.2: Factors considering for improvement of surface roughness.

Factors	Explanation
Concentration	Volume of Chemical in solution
Time	Exposure of Chemicals to parts
Temperature	Temperature of Solution
Surface Profile	Layer Thickness during part building

Four factors, listed above, were decided to improve the surface finish of the 3-D printed parts. Concentration was decided as the volume of chemical at varying levels for both the chemicals. The concentration levels for the Methyl Ethyl Ketone were 20%, 25%, 30% and 35% and concentration levels for Di-Methyl Ketone were 70%, 80%, 85% and 90% as these were the concentration were proven good for the ABS material.

The second factor was time as exposure of printed part to the chemical solution this also was varied for both the chemicals. Methyl Ethyl ketone was exposed to the produced part for 3 and 6 minutes and Di-Methyl ketone bath to the produced part was decided for 5 and 10 minutes. The third factor was temperature, one at the room temperature as 25 Celsius and then other at the higher temperature at 50 Celsius because these chemicals has higher diffusion rate at elevated temperatures. Last factor which was chosen was the surface profile which means the initial layer

thickness that is decided by the thickness of the material deposited at the time of extrusion. Different surface profile were selected to see if the chemicals' improvement rate gets affected with variation in thickness. Table 3.3 and Table 3.4 specify the different factors and their different level with the Methyl Ethyl Ketone and Di-Methyl Ketone (Acetone) respectively.

Table 3.3: Factors and their levels for experiment with MEK.

Sr. No	Name of the Factors	Level-1	Level-2	Level-3	Level-4
1	Concentration (percentage)	20%	25%	30%	35%
2	Time (minutes)	3 mins	6 mins		
3	Temperature (Celsius)	25˚C	50˚C		

Table 3.4: Factors and their levels for experiment with di-methyl ketone.

Sr. No	Name of the Factors	Level-1	Level-2	Level-3	Level-4
1	Concentration (percentage)	70%	80%	85%	90%
2	Time (minutes)	5 mins	10 mins	-	
3	Temperature (Celsius)	25˚C	50˚C		

3.11 PRE-ELIMINATION OF FACTORS IN IMPROVING SURFACE ROUGHNESS

These factors were considered first in improving the surface finish of the product as the above factors did the drastic improvement in the Acrylonitrile Butadiene Styrene (ABS) material. These factors were then used in the ULTEM material with the same levels thus there was no improvement with respected levels. The factors were kept at the varying levels so that change can be noticed if there is a change in the surface roughness of prototype otherwise the levels can be varied of different factors which can be considered. The factors were left the same changing the different levels for the preliminary work to notice if there is any change in the product. The new levels which were taken for consideration were 70%, 80%, 90% and 100% for Methyl-Ethyl-

Ketone (MEK) concentration levels, and took the same concentration levels for the Di-Methyl Ketone (Acetone). Time was increased to 90 minutes, 180 minutes, and 360 minutes to notice how the increase in time affected in improving the surface roughness of the product. Temperature was kept constant to 25 Celsius and 50 Celsius as the above mentioned chemicals (MEK and Acetone) react at the elevated temperatures thus keeping one at the room temperature and another at the increased level to see the difference. The Surface Profile was kept constant as noticing the change in the first three factors in the pre-elimination of factors and there levels.

Table 3.5: Factors and their levels for pre-elimination with Di-Methyl Ketone & MEK.

Sr. No	**Control Factors**	**Levels**			
		1	2	3	4
1	Concentration	70%	80%	90%	100%
2	Temperature	25 ˚C	50 ˚C		
3	Time	90 mins	180 mins	360 mins	

After performing the preliminary experiments there were some facts which came into consideration so that we can eliminate and keep focusing on other factors which are playing the major role in improving the surface roughness of the product. At the time of immersing the part in the Methyl Ethyl Ketone (MEK) solution there was a huge improvement that was noticed both at room temperature and at the elevated temperature respectively. Change in surface roughness was noticed at higher concentration more (90% and 100%). Improvement in surface roughness even happened with respect to time change. Methyl Ethyl Ketone solution changed its color at the elevated temperature and even the surface of the product changes its color from black to different layers of grey.

When the product is immersed in the Di-Methyl Ketone solution at any concentration at the elevated temperature, the product is loses its exterior color and surface roughness is also

improved but the solution at the elevated temperature is turns to vapors. As the solution is converted to vapors on elevating the temperature of the solution it change the process through which surface roughness improvement was planned, thus the following process is called Vaporization. Due to Vaporization which occur in the Di-Methyl Ketone solution at the elevated temperature the certain situation is being eliminated. There is not much improvement in the Di-Methyl Ketone at the room temperature when the part is immersed in the solution at different factors and at different levels which forces to eliminate the Di-Methyl Ketone Solution completely.

Table 3.6: Factors their levels, and how much surface improved with MEK

Sr. No	**Concentration**	**Time**	**Temperature**	**Surface roughness decreased**
1	100%	90 mins	50 ˚C	0.09136
2	100%	180 mins	50 ˚C	0.06329
3	100%	360 mins	50 ˚C	0.06059
4	100%	90 mins	25 ˚C	0.02004
5	100%	180 mins	25 ˚C	0.08404
6	100%	360 mins	25 ˚C	0.09116
7	90%	90 mins	50 ˚C	0.13314
8	90%	180 mins	50 ˚C	0.02877
9	90%	360 mins	50 ˚C	0.1413
10	90%	90 mins	25 ˚C	0.0076
11	90%	180 mins	25 ˚C	0.04388
12	90%	360 mins	25 ˚C	0.15819

While creating the product there is a deposition of molten plastic layer by layer to form the product required and it is built as the plastic solidifies. After the product is solidified there are lines on the product which can be observed with eyes clearly and is what’s causing the roughness

in the product. When the product is zoomed down, it is easily noticed that there is a valley kind of figure it is formed due to layer deposition and is known as the staircase effect. There are many ups and downs on the edge of the surface which increases the surface roughness of the part, in a way affecting different mechanical properties and changed the texture of the part.

The part desire is without those extra bulges on the edges and what is wanted is a straight line which can be seen at the end when zoomed. The distance which got reduced from that bulge to the edge of the surface is showed in the table and plotted on graph below with varying the different factors to different levels.

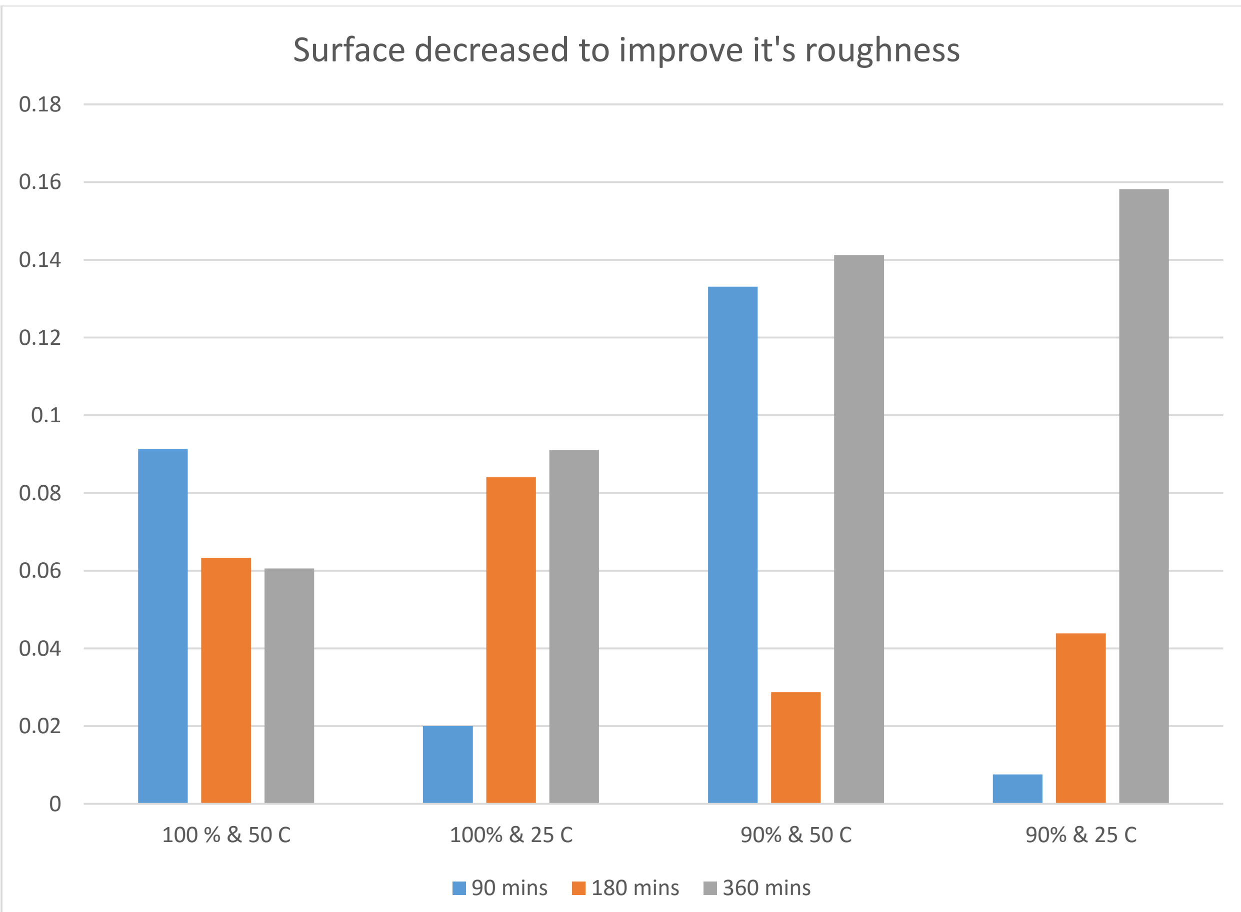


Figure 3.5: Surface decreased to improve its roughness.

Figure 3.6(a) ULTEM before MEK 100%, 3 hours, 25 C

Figure 3.6(b) ULTEM after MEK 100%, 3 hours, 25 C

Figure 3.6(c) ULTEM before MEK 100%, 3 hours, 50 C

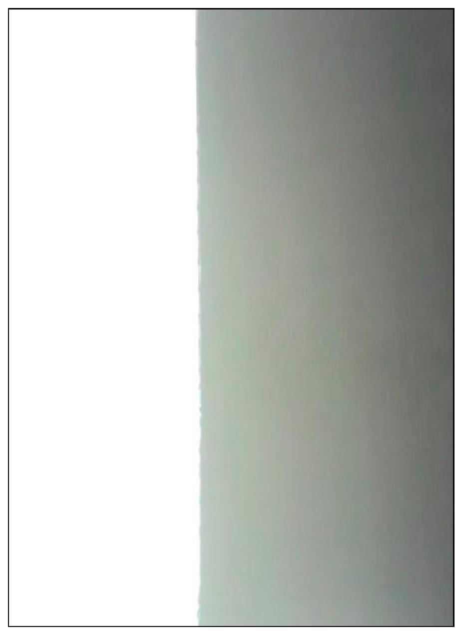


Figure 3.6(d) ULTEM after MEK 100%, 3 hours, 50 C

Figure 3.6: ULTEM after and before parts (pre-elementary parts)

The diagrams posted above (a) and (b) show the part before it was immersed in the MEK solution with 100% concentration, 3 hours at 25 Celsius and 50 Celsius respectively. Diagrams (c) and (d) show the ULTEM part after it was immersed in with 100% concentration, 3 hours at 25 Celsius and 50 Celsius respectively.

The distance which is reduced is directly proportional to improvement in the surface roughness. The above table clearly shows that each part showed the huge amount of improvement in the surface roughness when it is dipped in the chemical solution with the different concentration, varying with the temperature of the solution and the exposure of solution to the part for different time. The above experiments do not show the uniform result because the parts initial roughness was varied because parts were just cut down from the scrap material that is the reason behind having the variation in the result of improvement. In the final experiments the part will be built from the scratch so all the parts can have the same surface profile before starting of the experiment.

3.12 PROFILOMETER

Profilometer is a measuring device which is used to measure the surface profile of a product in the way to quantify the surface roughness. There are two types of profilometer i.e. surface of any product can be measured in two different ways by contacting the surface of part and other without contacting the surface i.e. through laser, lights etc.

Contact Profilometer

A diamond stylus in contact with the surface is moved on the surface first in a vertical direction and then laterally across the sample in a specific region and the mentioned contact force. A contact profilometer can also compute the small vertical displacement on the surface module by the vertical stylus displacement as a function of position. The height at which diamond stylus is generates an analog signal which is then converted to digital signals, then those signals are stored analyzed and displayed on screens. The range of the radius of the diamond stylus is between the

20-50 nanometers. As the radius of the stylus tip can be less than the 20 nanometers which has the prominent better results than the white light optical profiling as it uses the direct technique in the profilometer, thus no modelling is required. Scan speed and data signal sampling rate decides the horizontal resolution in the profilometer. The stylus tracking force varies from each of the profilometer accordingly. The results obtained from the contact profilometer is accepted in world in most of the regions. As the stylus of the contact profilometer is in contact with the product the method is not sensitive to surface reflectance or color or even if the measurement is taken in the dirty environments.

Non-Contact Profilometer

Non-Contact Profilometer is generally the optical profilometer which also provides the similar information as the contact profilometer. As the market competition is increasing there are many new techniques which keeps on adding in this type of profilometer. The new techniques that are being employed are laser triangulation sensors are employed to improve safety, confocal microscopy which is used for profiling of very small products, and low coherence interferometry which is a technique in which waves usually electromagnetic which are superimposed for the measurements of the small displacements, refractive index changes and surface irregularities. The major advantage of the non-contact profilometer is the scan speed which is done according to scan speed directed by the light reflected from the surface. Optical profilometer does not get damaged by surface wear or by the careless user as it does not get touched to the surface.

Chapter 4: Methodology

Due to global competition in the market there is the need of faster product development. Rapid Prototyping has been introduced to reduce the product development time drastically. Rapid Prototyping technique is used to fabricate the physical models which are used in visual inspection, ergonomic evaluation and form-fit analysis etc. Thus, to shorten the product development time Rapid Prototyping is emerging the most important technology. Amongst all the Rapid Prototyping technologies Fused Deposition Modelling is the most commonly used techniques. The materials used in Fused Deposition Modelling (FDM) is non-toxic, non-smelly and environmentally friendly which can be used as desktop prototyping which is the advantage of the Fused Deposition Modelling. There is a large variety of colors and materials available such as ULTEM, Acrylonitrile butadiene styrene (ABS) and casting wax. In Fused Deposition modelling, parts that are fabricated by Rapid prototyping technique they are not hygroscopic because they has a high stability.

Layered Manufacturing (LM) process is applied by most of the Rapid Prototyping technologies to fabricate the three dimensional physical models. One of the major disadvantages of the three dimensional object is Staircase effect which reduces the surface quality of the fused deposition modelling part. Therefore, for general engineering purposes surface finish of the fused deposition modelling is not satisfactory. Many researchers have intensively addressed to the surface quality of the part for the above reason as mentioned. Many researchers address the problem of surface roughness of fused deposition modelling parts like staircase machining or by using the optimal process parameters both the approaches are highly sophisticated. Some of the researchers also proposed an idea of abrasive flow machining and computer numerical control milling machines to improve the surface finish of the Rapid Prototyping parts the only disadvantage with these ideas is that it is more time consuming. The purpose of this research is to propose a simple approach for improving surface quality of ULTEM parts fabricated by Fused Deposition Modelling.

4.1 ULTEM 9085 PRINTING

The results of the pre-elimination clearly shows that there is the surface improvement in each of the parts which were immersed in the Methyl Ethyl Ketone solution with varying the different factors at different levels. The difference in the surface finish improvement was caused because the initial surface roughness of each product was different; thus, it is understood that solution with different parameters helps in improving the surface finish. To understand which parameter is playing the important role in improving surface finish or the interaction of parameters which is improving the surface roughness the most important thing which is having the initial surface roughness similar for each part. The part that needed to be built by the ULTEM 9085 material which can be immersed in the chemical solution is to be design. The side of the product that immerses in the solution

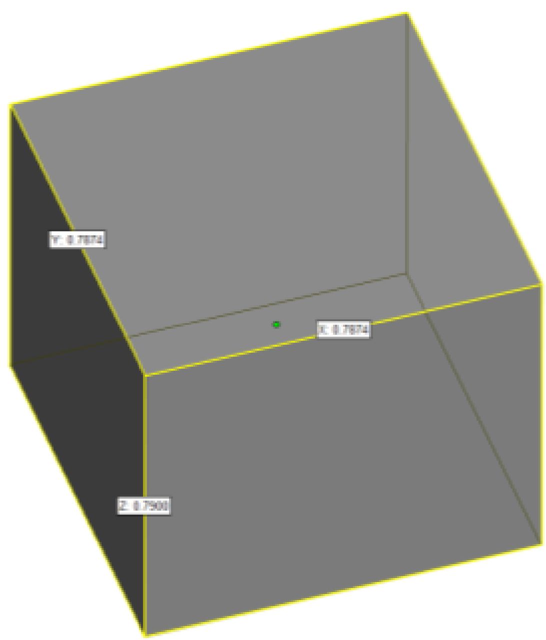


Figure 4.1: ULTEM part designed as a sample in solid works.

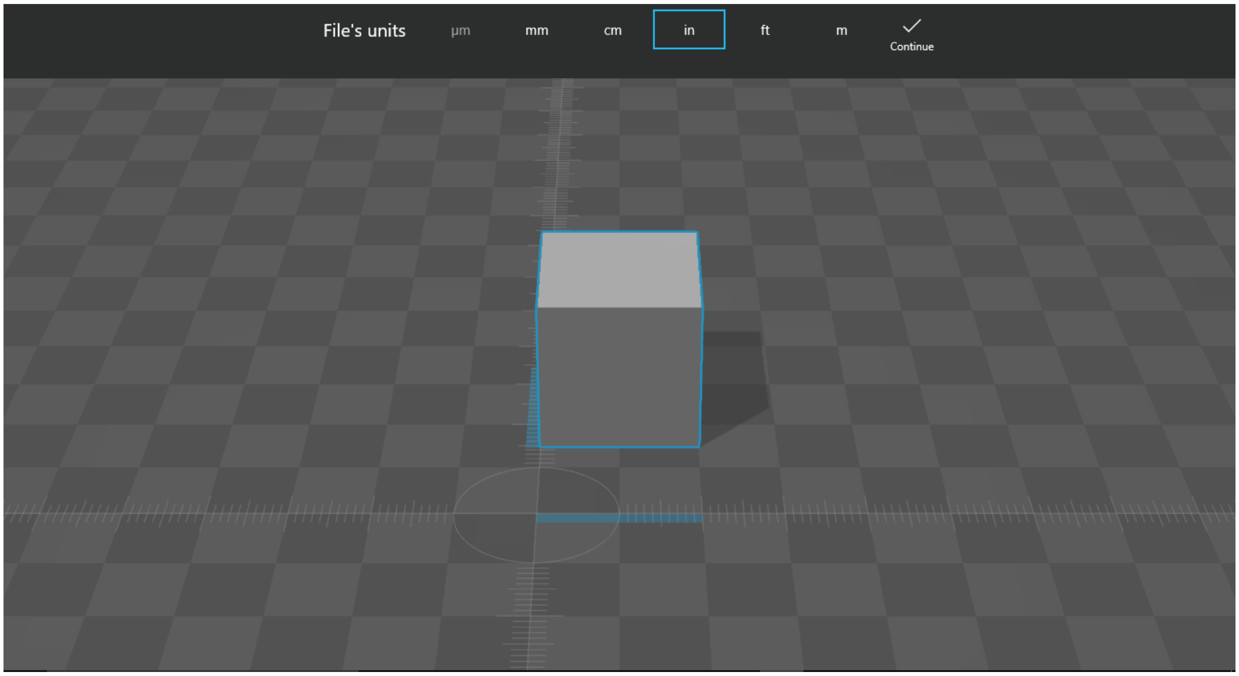


Figure 4.2: ULTEM sample in STL format.

The part is (shown in the figure 8) being designed at solid works to prepare it as a sample for the final experiments that needs to be conducted. The part is designed as a square with its all sides of 2 cm as the length of the part that is dipped in the solution is about 1 cm.

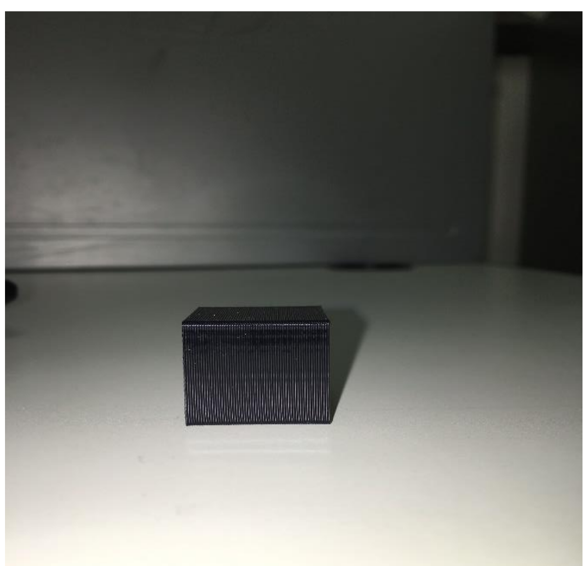


Figure 4.3: Optical image of ULTEM sample prepared in Keck center.

The part to print order is given in W. M. Keck center as the ULTEM 9085 is a special thermoplastic for which a specific functional printer is required that is Fortus 900 machine. Fortus 900 machine supports the 12 different type of thermoplastic including the ULTEM material and has the build size or chamber size where part is built is of dimensions 36*24*36 inches (914*610*914 mm). The part is built with 0.013 inches layer thickness. ULTEM 9085 is the best mix of mechanical, chemical and thermal properties. Insight software prepares the CAD program STL file to be manufactured on a Fortes system on its own slicing, creating its support structures and main materials extrusion paths. The operators can edit the different parameters that determines the look strength and accuracy of the part.

Figure 4.4: Optical image of Fortus 900 printer in Keck center.

4.2 STATISTICAL DESIGN OF EXPERIMENTS

The focus of the current chapter is to address the surface profile of the part that needs to be in chemicals with variant conditions, like different level of concentration, time for exposing to the

part, temperatures and initial (roughness) surface profile. The ANOVA technique will be used to find out the significant factors in improving the surface profile.

The Statistical Design of Experiments alludes to the procedure of planning the experiment so that appropriate data that can be understood by statistical method and will be gathered resulting in valid and objective conclusions. For gathering substantial and meaningful solution from an experimental design data a statistical tool is always preferred. To any of the experimental problems there are two approaches. One is the Design of Experiments and the other one is statistical analysis of data. When there are multiple number of factors that control the performance of any system, then it becomes essential to find the significant factors which might need the special attention to control or mainly optimize the system performance. Taguchi's concept of Orthogonal Array is one of the part of the Statistical Design of Experiments.

In our experiment there are many different factors which might play an important role in improving the surface profile. The Taguchi method was developed by Genichi Taguchi to improve the quality of the manufactured goods. Many statiscians have praised and welcomed the goals and improvement brought about by Taguchi. Taguchi's concept of Orthogonal Array can be implemented in our experiment to plan the set of experiments that need to be perform. After we perform all the experiments there is a need to find the significant factor i.e. to find the factor which played the most crucial role in improving the surface profile, we can use the ANOVA method to find out the most significant factor.

Genichi Taguchi has made some important contributions to statistics and engineering. His effect on loss to society, techniques for investigating of variation in experiments and his overall strategy of system, parameters and tolerance designs have been prominent in improving the quality of the manufactured quality worldwide. Even thereafter, there are some statistical aspects of Taguchi methods are in dispute, but nevertheless they are applied to the many different process.

This method has been successfully implemented in diverse areas such as government policymaking, Design of VLSI and even robust eco-design.

Taguchi made a huge number of innovations and also developed his experimental theories independently. The outlines planned to permit more prominent comprehension of variety as compared to traditional designs. He gave an idea of extending each experiment with an orthogonal array which should simulate the random environment in which product would function, many quality specialists have been using these orthogonal arrays.

The orthogonal Array plays an important role in development of Taguchi methods. It was successfully applied and implemented by Japanese and Indian industries and was also embraced by United States industries; now it is being applied by all the industries worldwide. Orthogonal Arrays represent a versatile class of combinations of arrangements necessary for conducting experiments to determine the optimum mix of number of factors in a product to maximize the yield. Taguchi's Orthogonal Array is a type of general Fractional Factorial Design. Fractional Factorial Design is based on a design matrix proposed by Taguchi and allows us to consider a selected subset of combinations of multiple factors at multiple levels. Orthogonal Arrays are balanced to ensure that all levels of all factors are considered equally. The factors can be evaluated independently of each other despite of fractionally of design.

There are many different orthogonal matrices designed by Taguchi which are selected according to the different number of factors considered for experiment and the maximum number of levels decided for factors to perform the experiment. Taguchi created orthogonal array to allow major comprehension of variety when compared with rest of the designs. Taguchi planned the idea of creating an orthogonal array which would adjust according to varying environment in which a product may work.

Table 4.1:-Design matrix of orthogonal array.

Number Of Parameters	Number of Levels				
		2	3	4	5
	2	L4	L9	L16	L25
	3	L4	**L9**	L16	L25
	4	L8	L9	L16	L25
	5	L8	L18	L16	L25
	6	L8	L18	L32	L25
	7	L8	L18	L32	L50
	8	L12	L18	L32	L50
	9	L12	L27	L32	L50
	10	L12	L27	L32	L50
	11	L12	L27		L50
	12	L16	L27		L50
	13	L16	L27		
	14	L16	L36		
	15	L16	L36		
	16	L32	L36		
	17	L32	L36		
	18	L32	L36		
	19	L32	L36		
	20	L32	L36		
	21	L32	L36		
	22	L32	L36		
	23	L32	L36		
	24	L32			

4.3 OGP

OGP is a device which has all the techniques require in the future trends for measurement of the object. The demand in the market for the complex product is increasing day by day like measuring a vast array of features without any of the two jobs being the same. OGP provides all the techniques in which two different types of measurement can be plotted down which has completely different measuring features it is only possible with the multi-sensor which is provided in it for measuring of any type of measurement requirement. OGP smart scope can perform functions for many of the different machines like Coordinate Measuring Machine (CMM), a laser scanner and a profilometer. OGP also reduces the cost of buying number of different machines, it also reduces calibrating and maintenance of these machines and thus eventually, provide some floor space in the company. As there are many multi-sensors installed on one machine there is a high level of inspection that take place on it. On a single machine when the part is taken for measurement, all the different parameters can be calculated and measured thus leading in reducing the lead time of part to be taken to different machines and reduce the human factor.

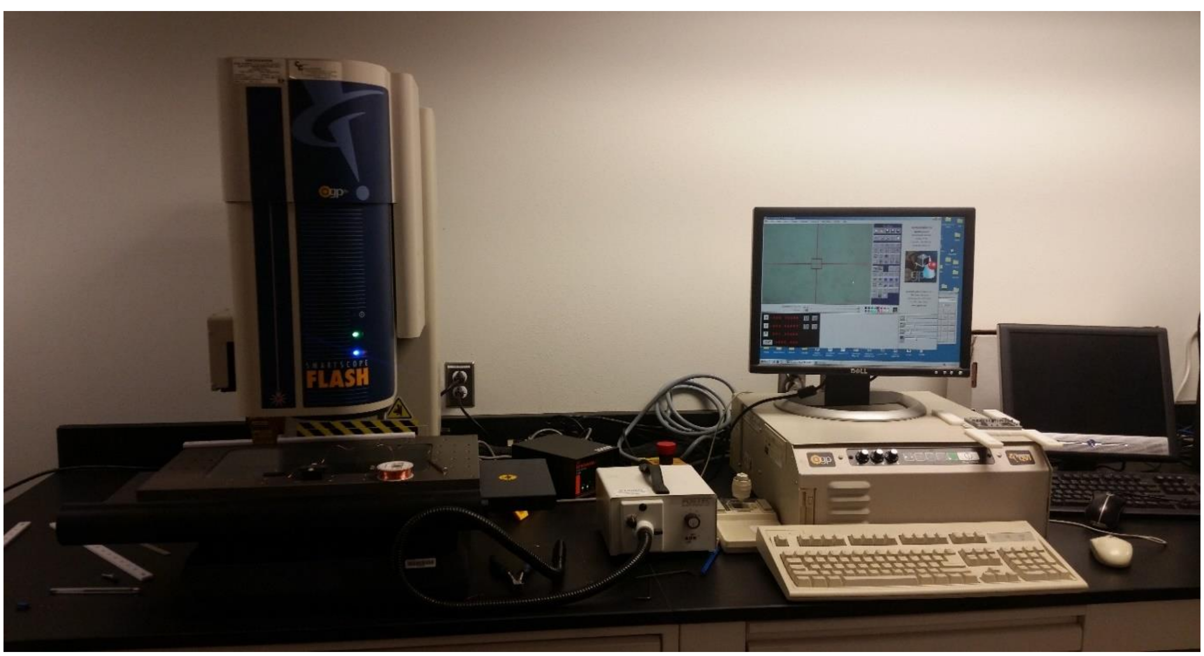


Figure 4.5: Optical image of OGP.

OGP measure all the measurements on it and report all the parameters in highly sophisticated manner. Floor model Smart-scope system is installed with servo-driven motorized stages which can be moved in XYZ plane which gives the feel for the actual floor shop and can be measured for completely automated inspection or measurement. A large engineered travel stage which can travel in XY plane is made with the robust bearing design and performance for the measurement of large parts. Automatic zoom lens is installed in it which focuses the part in the zoom range and it also help in image down the part to characterize all the qualities in a single setup though it has the accuracy rate of 67% as it is image focused not profile based.

4.4 FUME HOOD

Fume hood is a type of device which controls the exposure of harmful chemicals, toxic fumes and vapors of hazardous chemicals when chemicals are heated. Fume hood is a type of ventilation, it is a device which is enclosed by the five sides of work area but bottom of it is opened at the standard height of a standing position so that the worker can work in the desired environment. There are two types of fume hood ducted and recirculating but both of them work on the similar principle in which air is drawn from the open side of the cabinet and released in the outer environment of building or filtered through multiple procedures and released back into the lab. There are multiple functions of Fume hood generally all of them come under safety of the user they are, protecting user from inhaling harmful gases, protect the product on which experiment is conducted, protect the environment from chemicals. Secondly, it is also used to protect user from spill containment and any kind of explosion occur during the experiment. The fume hood is attached with the glass window which is generally called sash window and it is also attached with the light inside because it gets dim inside generally while performing experiments to get the accurate measurements or readings.

Figure 4.6: Optical image of fume hood.

4.5 EXPERIMENT MODEL CONSTRUCTION

To perform the final experiments the data is taken from the pre-elimination experiments. Methyl ethyl ketone is the only safe and effective chemical left which was selected according to the pre-elimination experiments where it showed drastic improvement in the different parameters

and there levels. The different parameters which were chosen for the final experiments were concentration of the solution, which was kept at 90% and 100%, time of exposure of the solution to the product was selected which was chosen at 90, 180 and 360 minutes and last parameter is temperature of the solution and selected temperatures were 25 and 50 Celsius. The part was placed in with the combination of different factors as shown in table below to find the optimum condition of improving the part surface roughness.

Table 4.2: Parameters in final model.

Sr. No	Concentration	Time	Temperature
1	90%	90 mins	50 ˚C
2	90%	180 mins	50 ˚C
3	90%	360 mins	50 ˚C
4	90%	90 mins	25 ˚C
5	90%	180 mins	25 ˚C
6	90%	360 mins	25 ˚C
7	100%	90 mins	50 ˚C
8	100%	180 mins	50 ˚C
9	100%	360 mins	50 ˚C
10	100%	90 mins	25 ˚C
11	100%	180 mins	25 ˚C
12	100%	360 mins	25 ˚C

Chapter 5: Case Study

5.1 Experiment Model Validation

After performing the preliminary experiments there were some facts which came into consideration so that we can eliminate few chemicals and reduce the levels which dint showed improvements. The priority is given to factors which are playing the major role in improving the surface roughness of the product at different levels.

At the time of immersing the part in the Methyl Ethyl Ketone (MEK) solution there was a major surface improvement that was noticed both at room temperature and at the elevated temperature respectively. Change in surface roughness was noticed at higher concentration more (90% and 100%). Improvement in surface roughness even happened with respect to time change.

While performing the final experiment there are few other parameters to consider for reaching the final result. There is the need of replication of experiments that should be done to come to any final conclusion. Each experiment individually were performed five different times so that if anything went wrong while performing experiments it can be neglected accordingly and there will be multiple readings to support the conclusion.

Multiple experiments were conducted keeping parameters and their levels same five different time and then the final readings were taken down at OGP. As performing the experiments it won't give us the exact same measurement for each of the product, thus it will give us the range around which those parameters at the respected level will improve the surface roughness.

The experiments need to be randomized also because it is important to see that the different factors at varying levels improve the surface roughness within the same range. The experiments were performed in the random order as it came along while randomizing the order. The order in which the experiments are performed are in the table below.

Table 5.1: Experimental order after randomization

Sr. No	Concentration	Time	Temperature
1	90%	90 mins	50 ˚C
2	100%	90 mins	25 ˚C
3	90%	360 mins	50 ˚C
4	100%	360 mins	50 ˚C
5	100%	180 mins	25 ˚C
6	90%	90 mins	25 ˚C
7	100%	360 mins	50 ˚C
8	100%	360 mins	25 ˚C
9	100%	360 mins	25 ˚C
10	90%	360 mins	50 ˚C
11	90%	180 mins	25 ˚C
12	100%	180 mins	50 ˚C
13	90%	90 mins	25 ˚C
14	100%	90 mins	25 ˚C
15	100%	90 mins	50 ˚C
16	100%	180 mins	50 ˚C
17	100%	360 mins	25 ˚C
18	100%	90 mins	50 ˚C
19	90%	90 mins	50 ˚C
20	100%	180 mins	50 ˚C
21	100%	360 mins	50 ˚C
22	90%	360 mins	50 ˚C
23	100%	90 mins	50 ˚C
24	90%	180 mins	25 ˚C
25	100%	360 mins	50 ˚C
26	100%	180 mins	25 ˚C
27	90%	360 mins	25 ˚C
28	90%	360 mins	25 ˚C
29	100%	360 mins	50 ˚C
30	90%	180 mins	50 ˚C
31	100%	90 mins	25 ˚C
32	90%	180 mins	25 ˚C
33	90%	90 mins	50 ˚C
34	100%	180 mins	50 ˚C
35	100%	90 mins	25 ˚C
36	90%	180 mins	25 ˚C
37	100%	180 mins	25 ˚C
38	100%	360 mins	25 ˚C
39	90%	360 mins	50 ˚C
40	90%	180 mins	50 ˚C

41	90%	180 mins	50 ˚C
42	100%	180 mins	25 ˚C
43	100%	90 mins	50 ˚C
44	90%	90 mins	25 ˚C
45	100%	180 mins	50 ˚C
46	90%	90 mins	25 ˚C
47	100%	180 mins	25 ˚C
48	90%	360 mins	50 ˚C
49	90%	360 mins	25 ˚C
50	100%	90 mins	50 ˚C
51	90%	360 mins	25 ˚C
52	90%	180 mins	50 ˚C
53	90%	90 mins	25 ˚C
54	100%	90 mins	25 ˚C
55	90%	90 mins	50 ˚C
56	90%	180 mins	50 ˚C
57	90%	180 mins	25 ˚C
58	90%	90 mins	50 ˚C
59	90%	360 mins	25 ˚C
60	100%	360 mins	25 ˚C

5.2 OGP Analysis

After the experiment is performed in fume hood with all the replications and randomizing the conditions the part is taken to the OGP machine to calculate the improvement in surface roughness of a product. The surface roughness is the distance between top node and its adjacent bottom node. The major purpose of this experiment is to get the flat surface of the product. Below we can see the final surface roughness value after the experiment was performed and the optical images of the part along the zoomed images captured from OPG.

Pre-Treatment Measurement

In pre-elimination experiments all the parts were scraped out from different products thus, they all have different initial surface roughness. To find the optimum condition for improving the surface roughness all the parts must have the same initial surface roughness. The new parts was thus printed for the successful run of the experiments. The side view of the part before the experiment along with the initial surface roughness measurement is shown in figure below. The

initial surface roughness measurement is 0.15923. There was a change in dimensions that was noted at the elevated temperature.

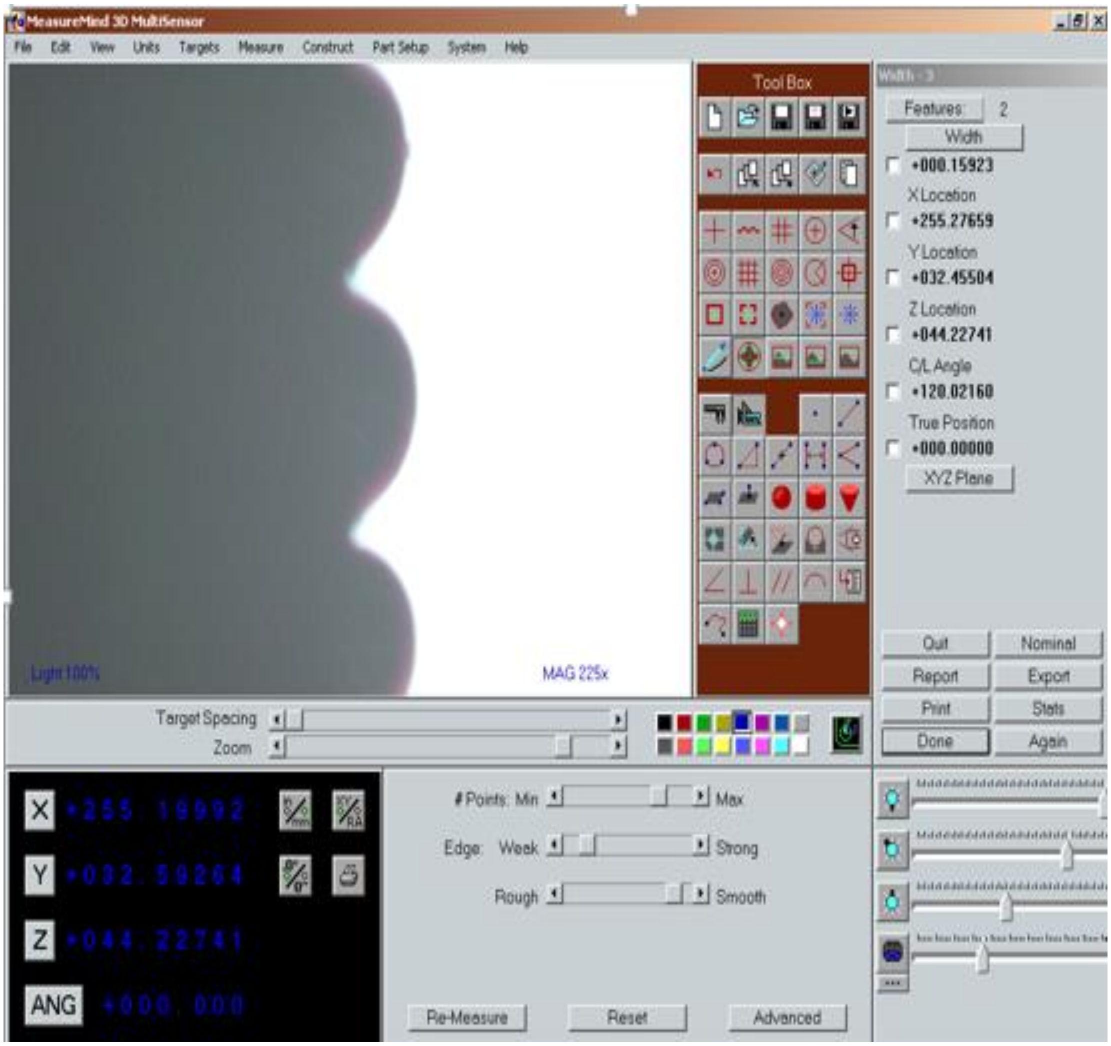


Figure 5.1: Initial surface roughness measurement.

CASE 1:- 90 % concentration, 90 minutes and 25 Celsius

In this case the product is immersed in the 90 percent Methyl Ethyl Ketone solution, for 90 minutes and at the room temperature at 25 Celsius. Below are the scanned and optical images of all the images and the final surface profile reading using OGP machine.

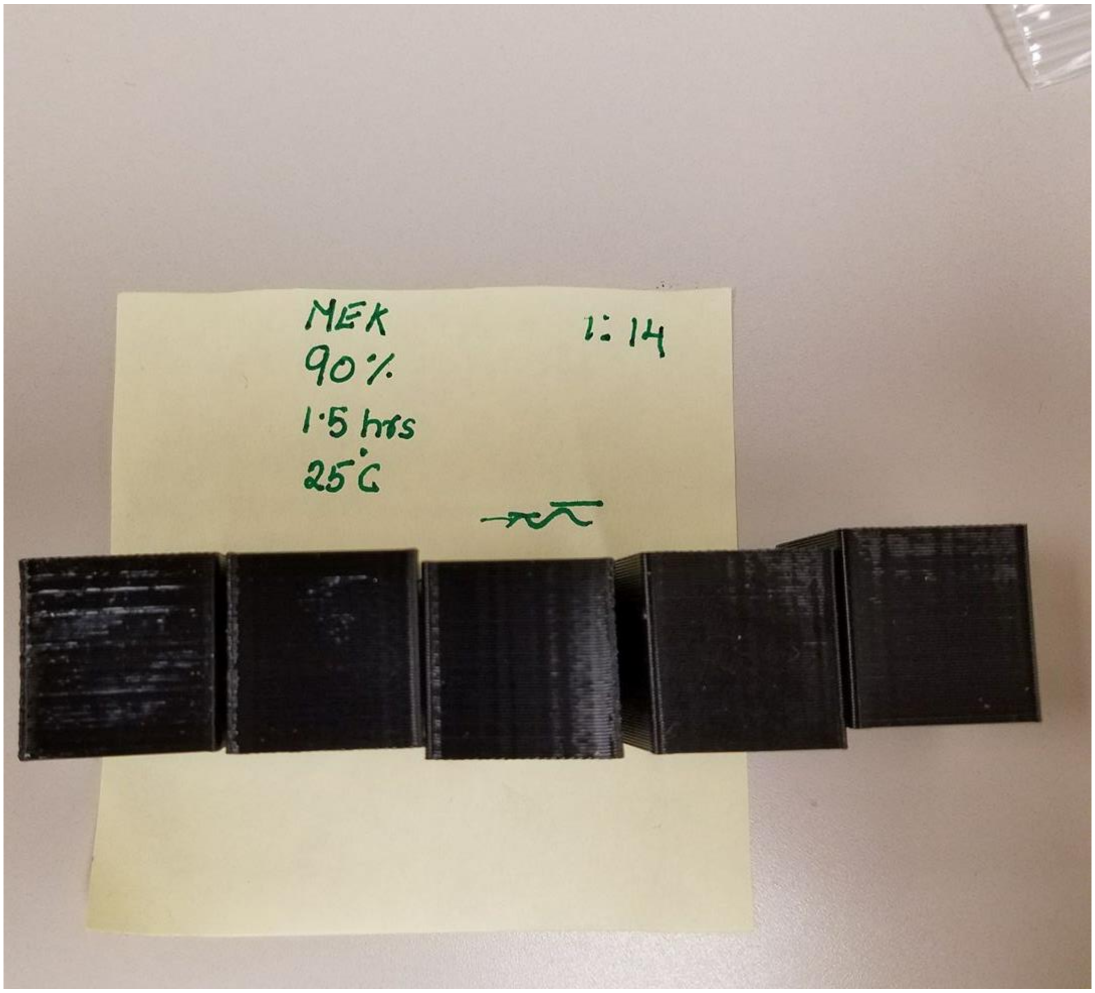


Figure 5.2(a): Optical image of post experiment for Case 1.

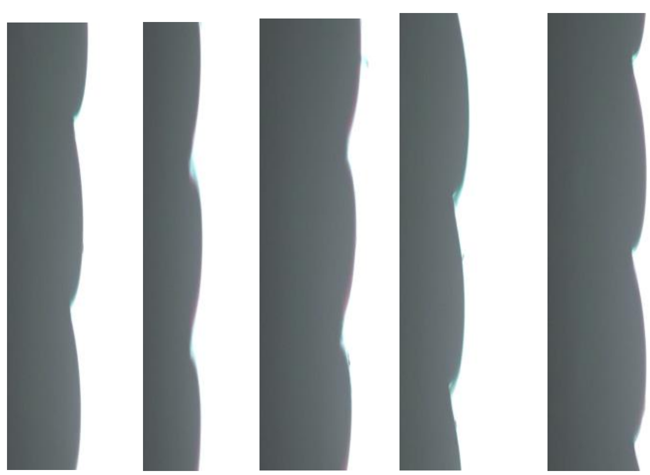


Figure 5.2(b): Scanned Images of post treatment from OGP for Case 1.

Table 5.2: Sample surface profile after Case 1.

Sample	Surface profile
Sample 1	0.00624
Sample 2	0.00666
Sample 3	0.02035
Sample 4	0.01529
Sample 5	0.00337

CASE 2:- 90 % concentration, 180 minutes and 25 Celsius

In this case the product is immersed in the 90 percent Methyl Ethyl Ketone solution, for 180 minutes and at the room temperature at 25 Celsius. Below are the scanned and optical images of all the images and the final surface profile reading using OGP machine.

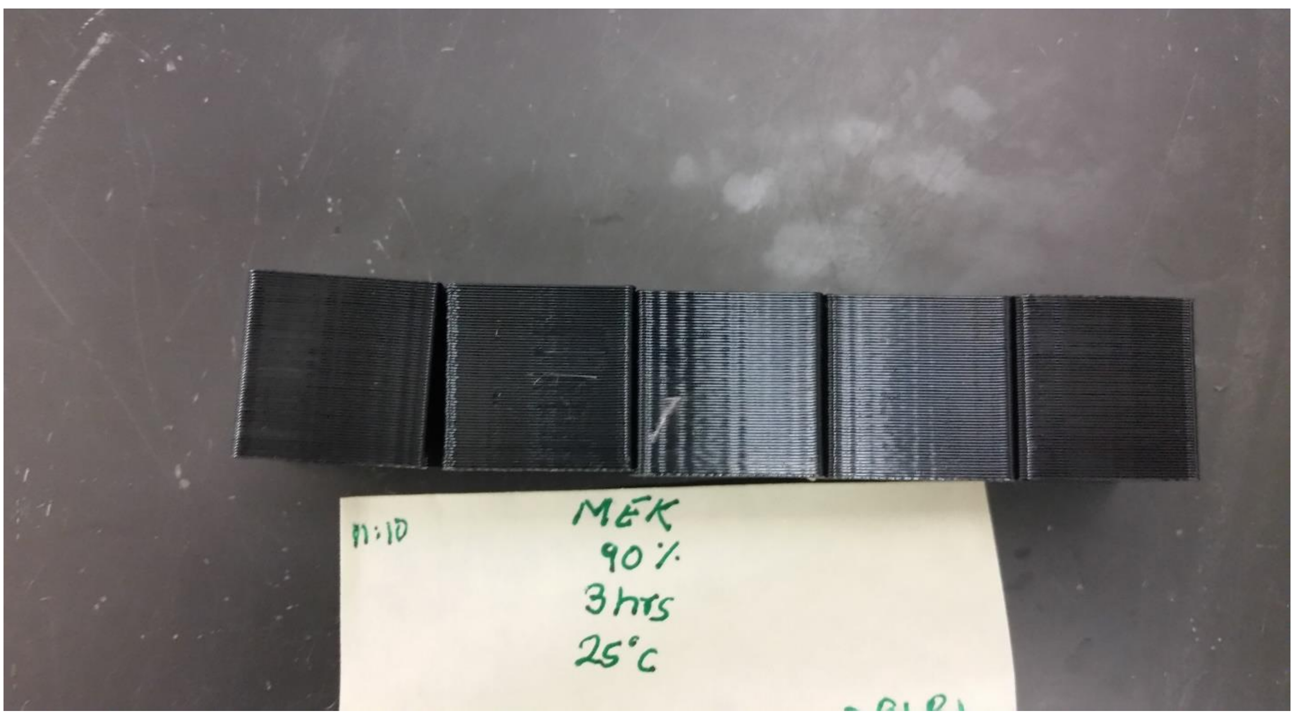


Figure 5.3 (a): Optical image of post experiment for Case 2.

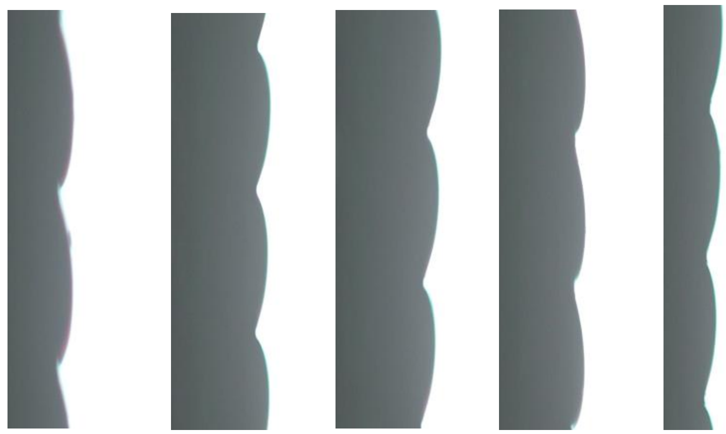


Figure 5.3(b): Scanned Images of post treatment from OGP for Case 2

Table 5.3: Sample surface profile after Case 2

Sample	Surface profile
Sample 1	0.01463
Sample 2	0.00396
Sample 3	0.00991
Sample 4	0.01172
Sample 5	0.00468

CASE 3:- 90 % concentration, 360 minutes and 25 Celsius

In this case the product is immersed in the 90 percent Methyl Ethyl Ketone solution, for 360 minutes and at the room temperature at 25 Celsius. Below are the scanned and optical images of all the images and the final surface profile reading using OGP machine.

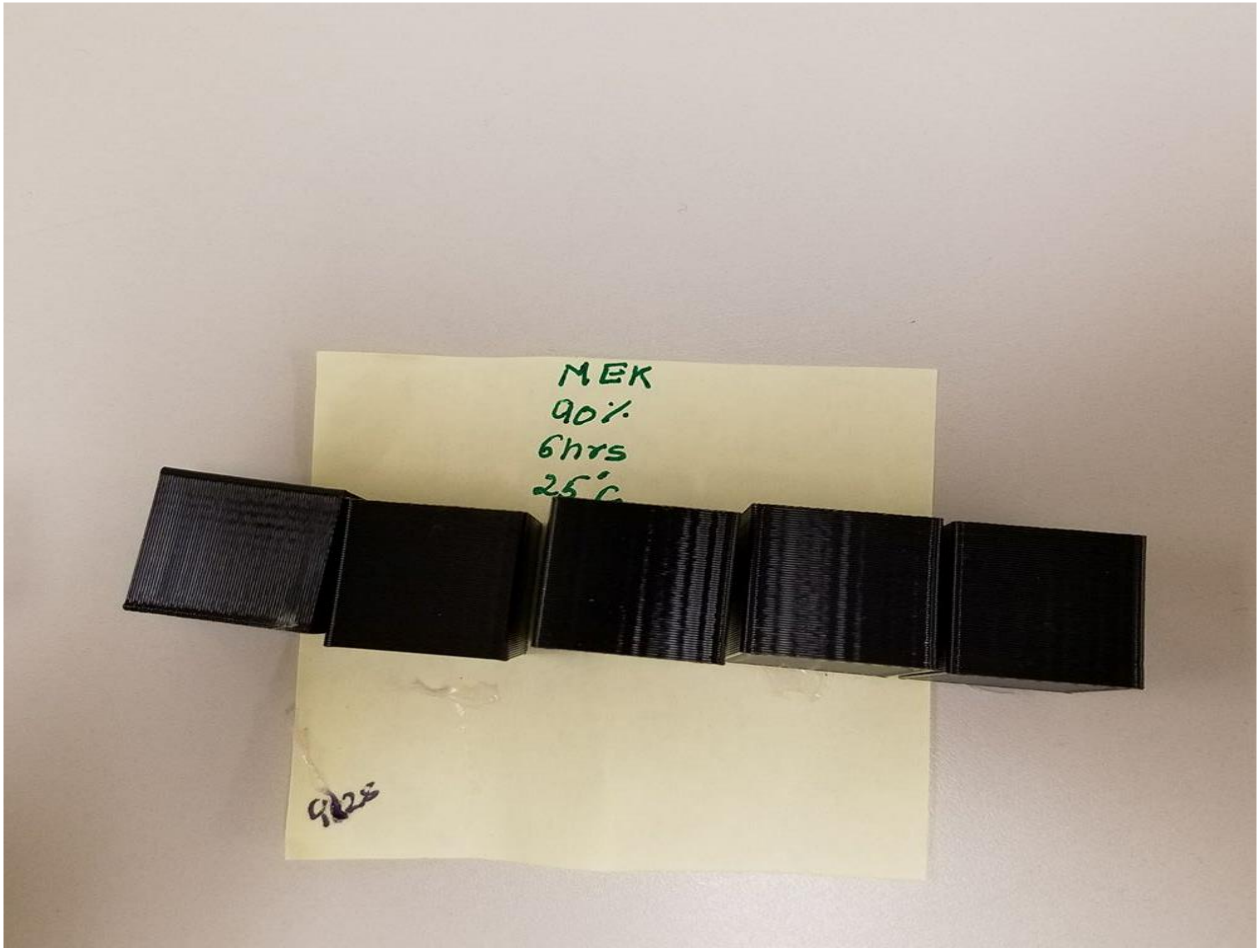


Figure 5.4(a): Optical image of post experiment for Case 3.

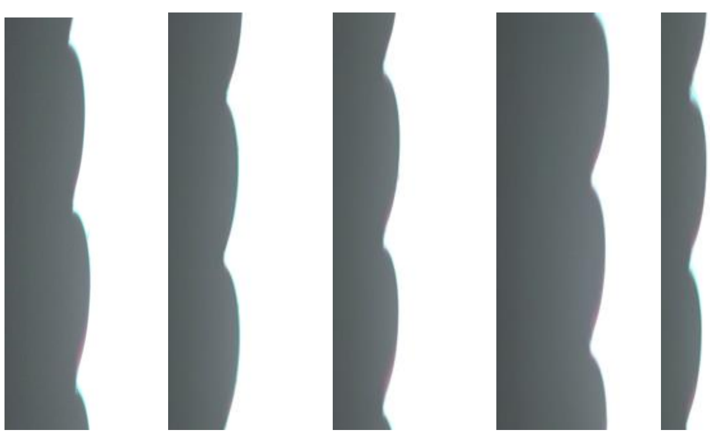


Figure 5.4(b): Scanned Images of post treatment from OGP for Case 3.

Table 5.4: Sample surface profile after Case 3

Sample	Surface profile
Sample 1	0.01191
Sample 2	0.02067
Sample 3	0.05715
Sample 4	0.00686
Sample 5	0.00152

CASE 4:- 90 % concentration, 90 minutes and 50 Celsius

In this case the product is immersed in the 90 percent Methyl Ethyl Ketone solution, for 90 minutes and at the elevated temperature at 50 Celsius. Below are the scanned and optical images of all the images and the final surface profile reading using OGP machine.

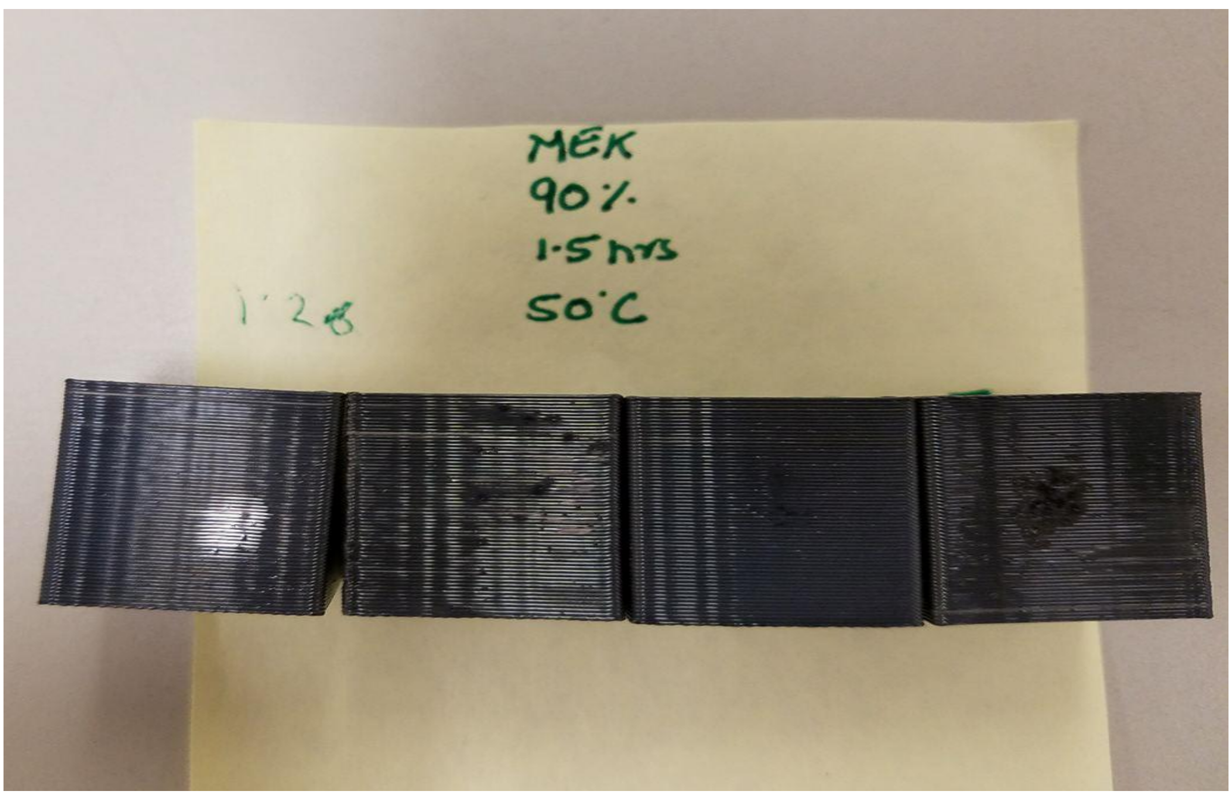


Figure 5.5(a): Optical image of post experiment for Case 4

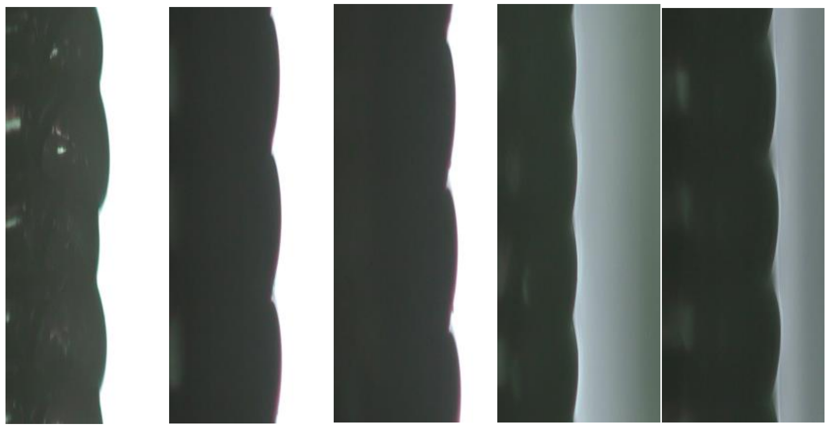


Figure 5.5(b): Scanned Images of post treatment from OGP for Case 4

Table 5.5: Sample surface profile after Case 4

Sample	Surface profile
Sample 1	0.09358
Sample 2	0.12035
Sample 3	0.10076
Sample 4	0.10597
Sample 5	0.00726

CASE 5:- 90 % concentration, 180 minutes and 50 Celsius

In this case the product is immersed in the 90 percent Methyl Ethyl Ketone solution, for 180 minutes and at the elevated temperature at 50 Celsius. Below are the scanned and optical images of all the images and the final surface profile reading using OGP machine.

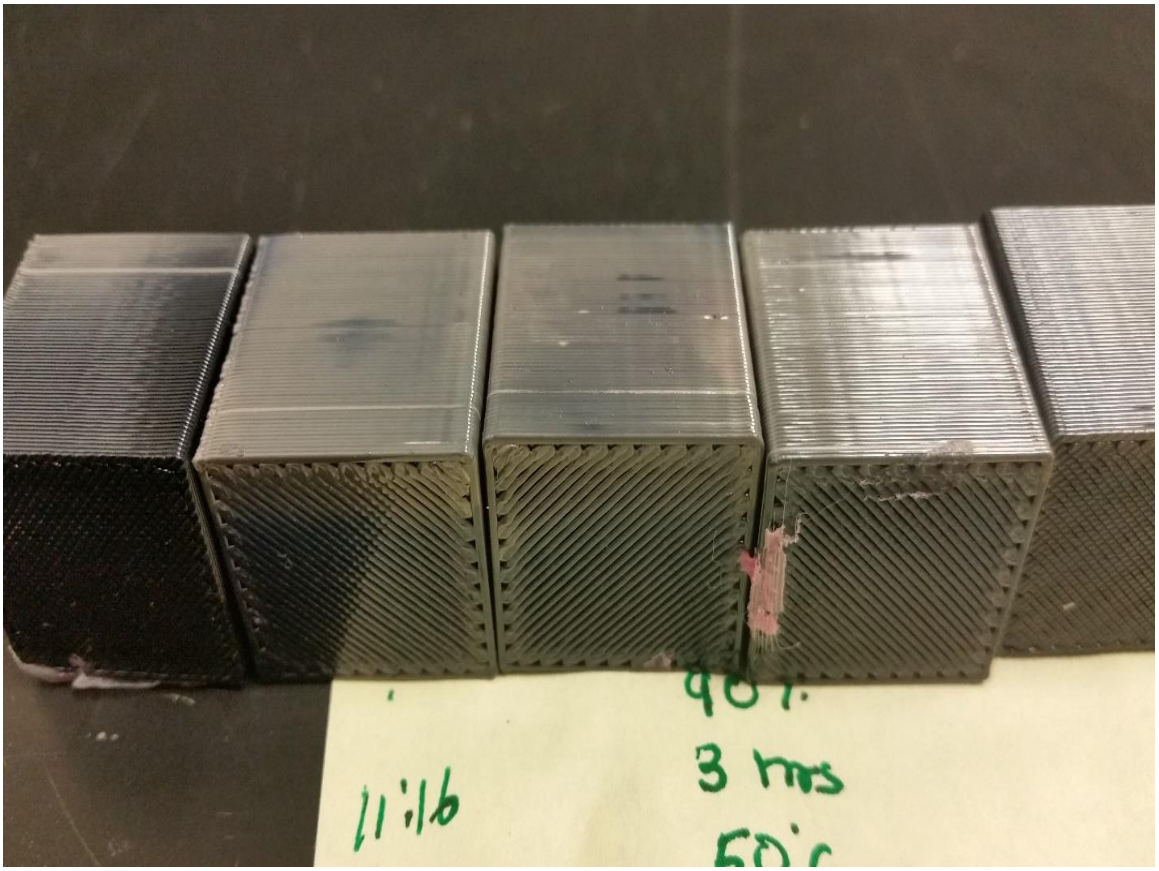


Figure 5.6(a): Optical image of post experiment for Case 5.

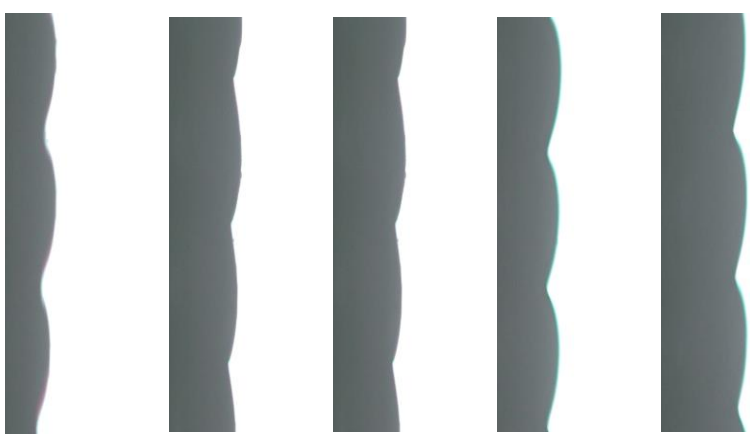


Figure 5.6(b): Scanned Images of post treatment from OGP for Case 5.

Table 5.6: Sample surface profile after Case 5

Sample	Surface profile
Sample 1	0.00099
Sample 2	0.00546
Sample 3	0.00127
Sample 4	0.01011
Sample 5	0.00150

CASE 6:- 90 % concentration, 360 minutes and 50 Celsius

In this case the product is immersed in the 90 percent Methyl Ethyl Ketone solution, for 360 minutes and at the elevated temperature at 50 Celsius. Below are the scanned and optical images of all the images and the final surface profile reading using OGP machine.

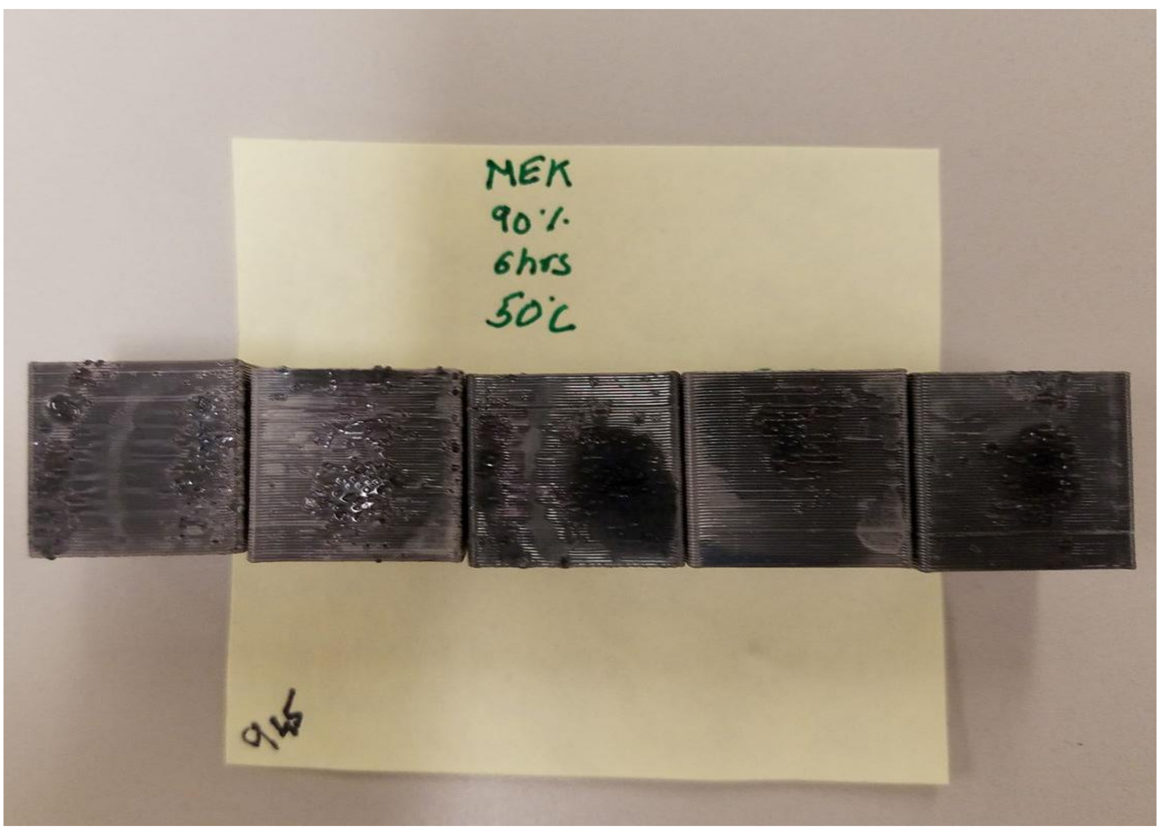


Figure 5.7(a): Optical image of post experiment for Case 6.

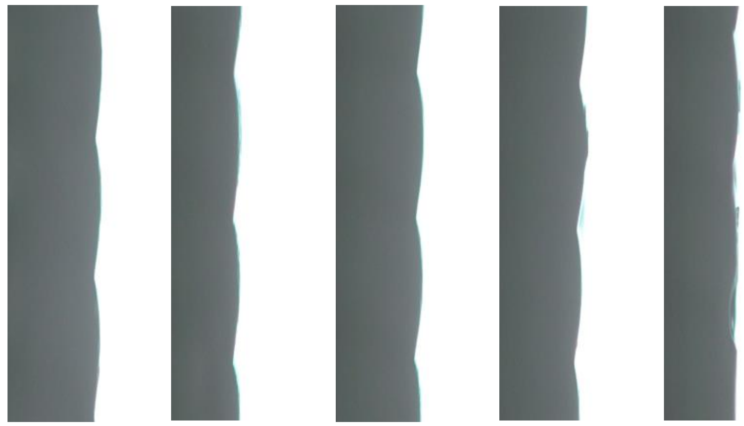


Figure 5.7(b): Scanned Images of post treatment from OGP for Case 6.

Table 5.7: Sample surface profile after Case 6

Sample	**Surface profile**
Sample 1	0.05165
Sample 2	0.03302
Sample 3	0.01301
Sample 4	0.12341
Sample 5	0.02761

CASE 7:- 100 % concentration, 90 minutes and 25 Celsius

In this case the product is immersed in the 100 percent Methyl Ethyl Ketone solution, for 90 minutes and at the room temperature at 25 Celsius. Below are the scanned and optical images of all the images and the final surface profile reading using OGP machine.

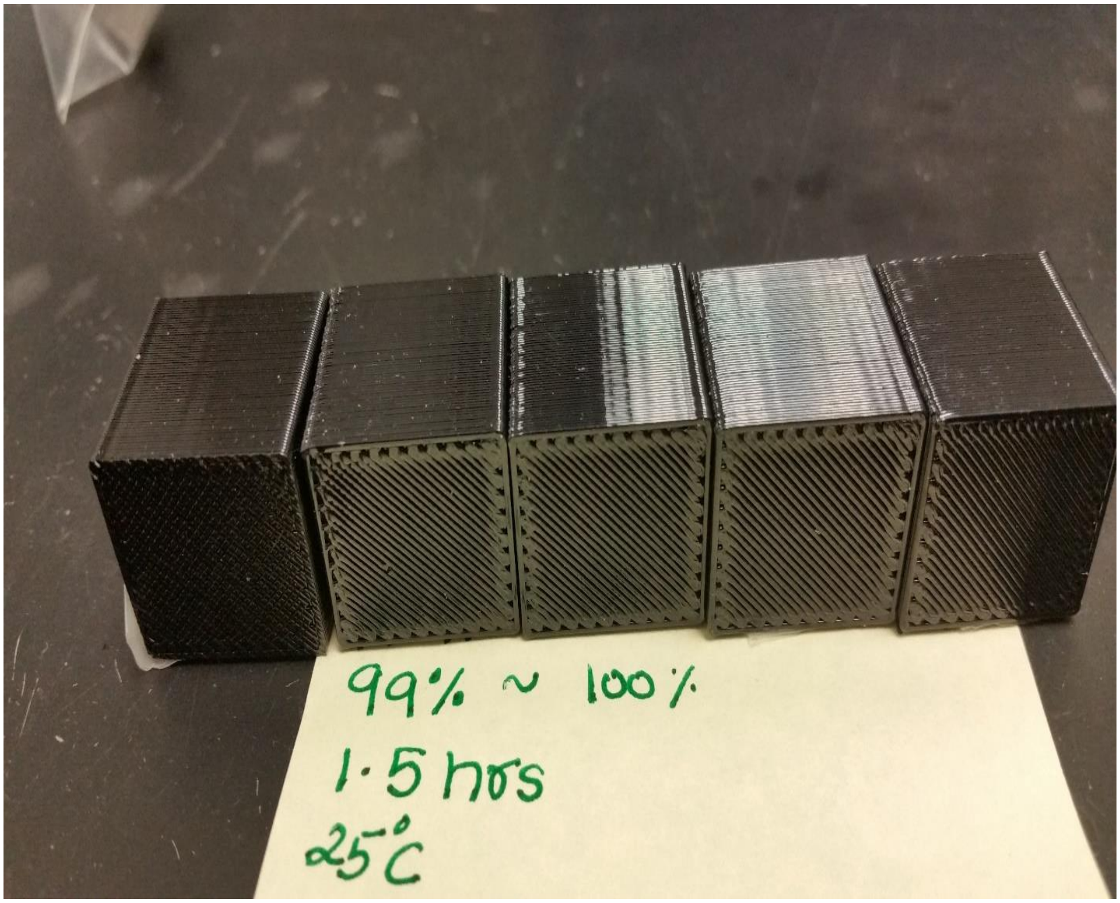


Figure 5.8(a): Optical image of post experiment for Case 7.

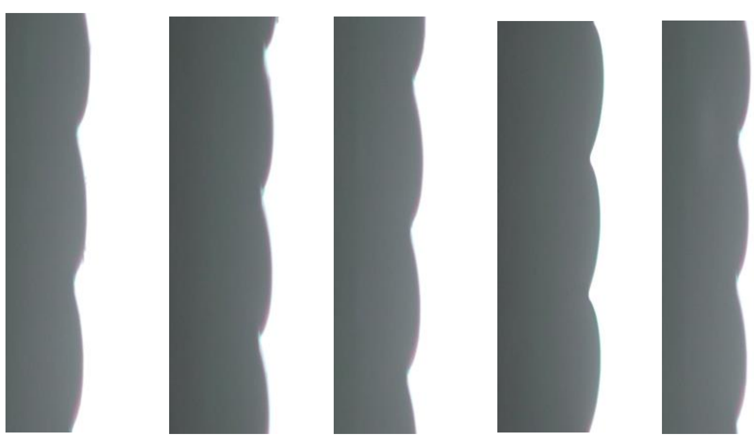


Figure 5.8(b): Scanned Images of post treatment from OGP for Case 7.

Table 5.8: Sample surface profile after Case 7

Sample	Surface profile
Sample 1	0.00187
Sample 2	0.13708
Sample 3	0.00170
Sample 4	0.00287
Sample 5	0.00241

CASE 8:- 100 % concentration, 180 minutes and 25 Celsius

In this case the product is immersed in the 100 percent Methyl Ethyl Ketone solution, for 180 minutes and at the room temperature at 25 Celsius. Below are the scanned and optical images of all the images and the final surface profile reading using OGP machine.

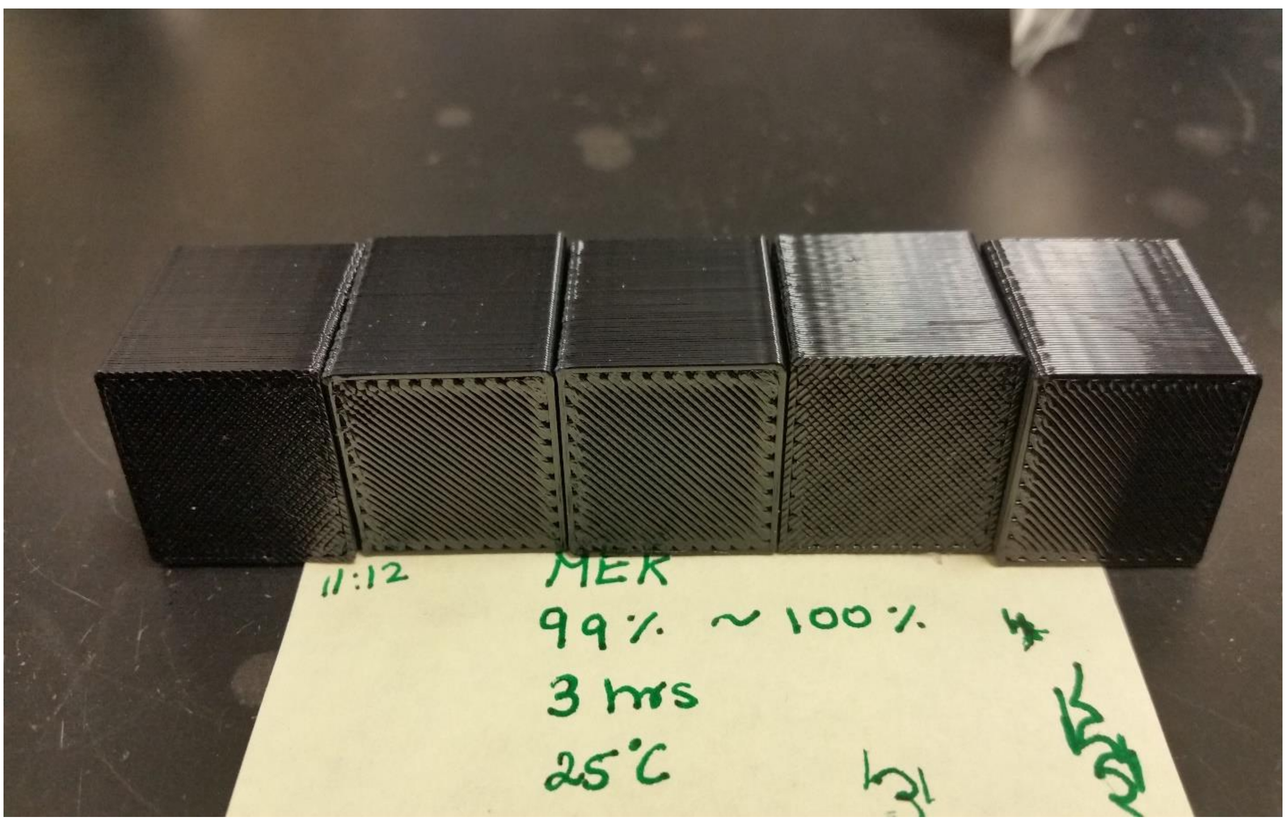


Figure 5.9(a): Optical image of post experiment for Case 8.

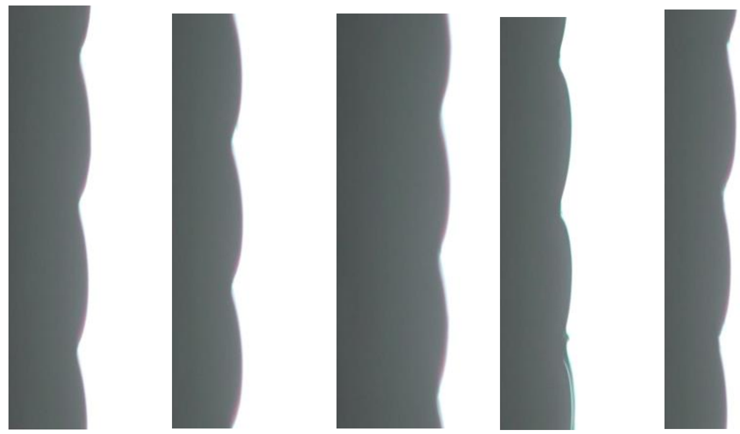


Figure 5.9(b): Scanned Images of post treatment from OGP for Case 8

Table 5.9: Sample surface profile after Case 8

Sample	Surface profile
Sample 1	0.00217
Sample 2	0.00562
Sample 3	0.01079
Sample 4	0.04349
Sample 5	0.03553

CASE 9:- 100 % concentration, 360 minutes and 25 Celsius

In this case the product is immersed in the 100 percent Methyl Ethyl Ketone solution, for 360 minutes and at the room temperature at 25 Celsius. Below are the scanned and optical images of all the images and the final surface profile reading using OGP machine.

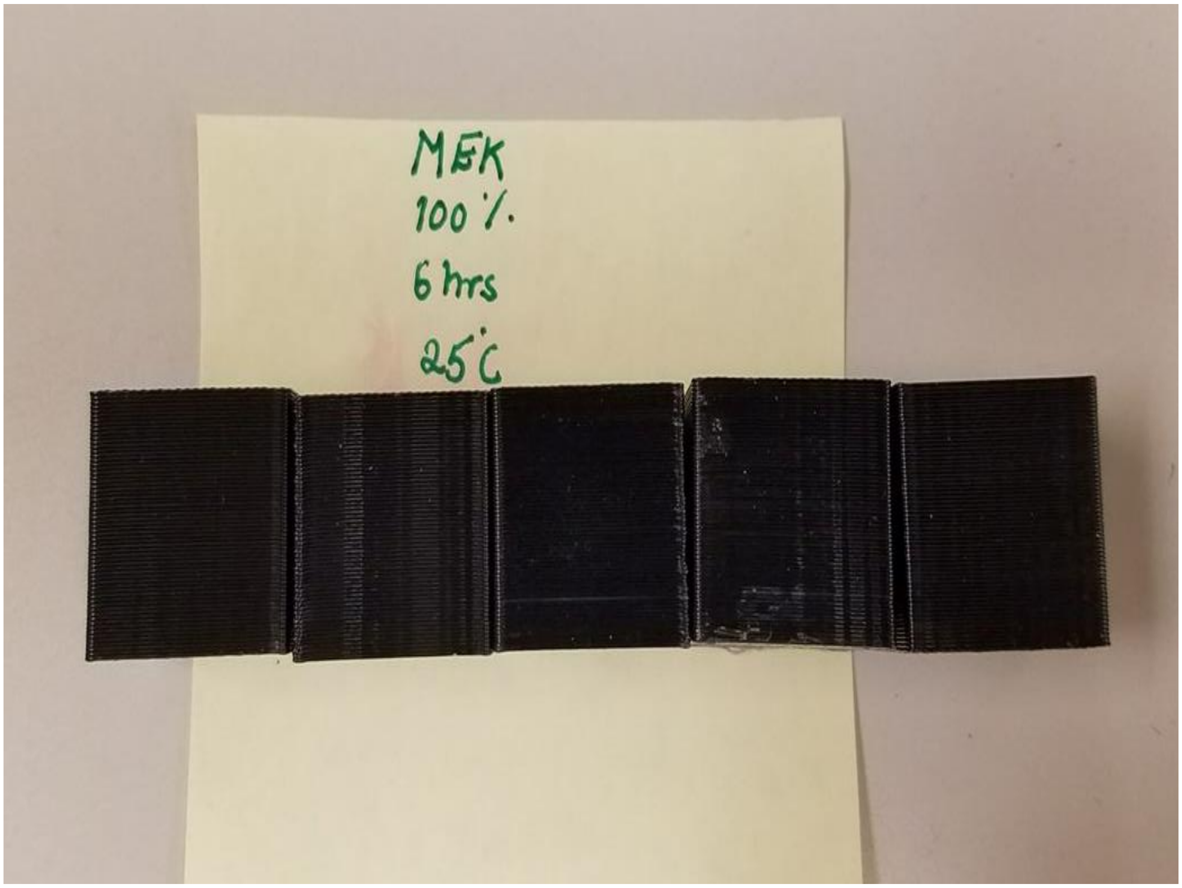


Figure 5.10(a): Optical image of post experiment for Case 9.

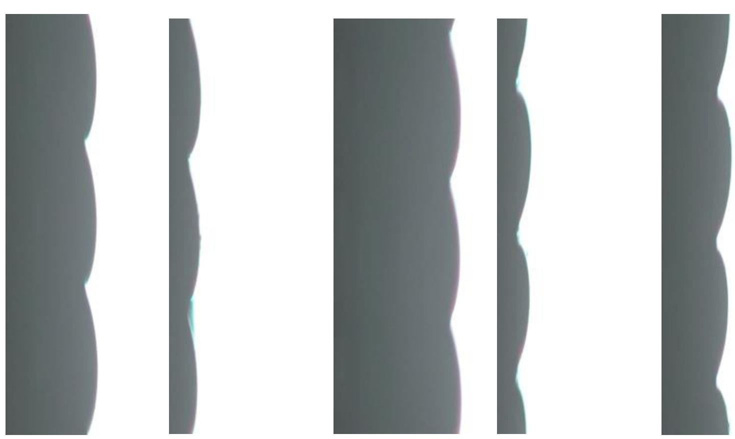


Figure 5.10(b): Scanned Images of post treatment from OGP for Case 9.

Table 5.10: Sample surface profile after Case 9

Sample	Surface profile
Sample 1	0.00483
Sample 2	0.00391
Sample 3	0.00296
Sample 4	0.00654
Sample 5	0.000516

CASE 10:- 100 % concentration, 90 minutes and 50 Celsius

In this case the product is immersed in the 100 percent Methyl Ethyl Ketone solution, for 90 minutes and at the elevated temperature at 50 Celsius. Below are the scanned and optical images of all the images and the final surface profile reading using OGP machine.

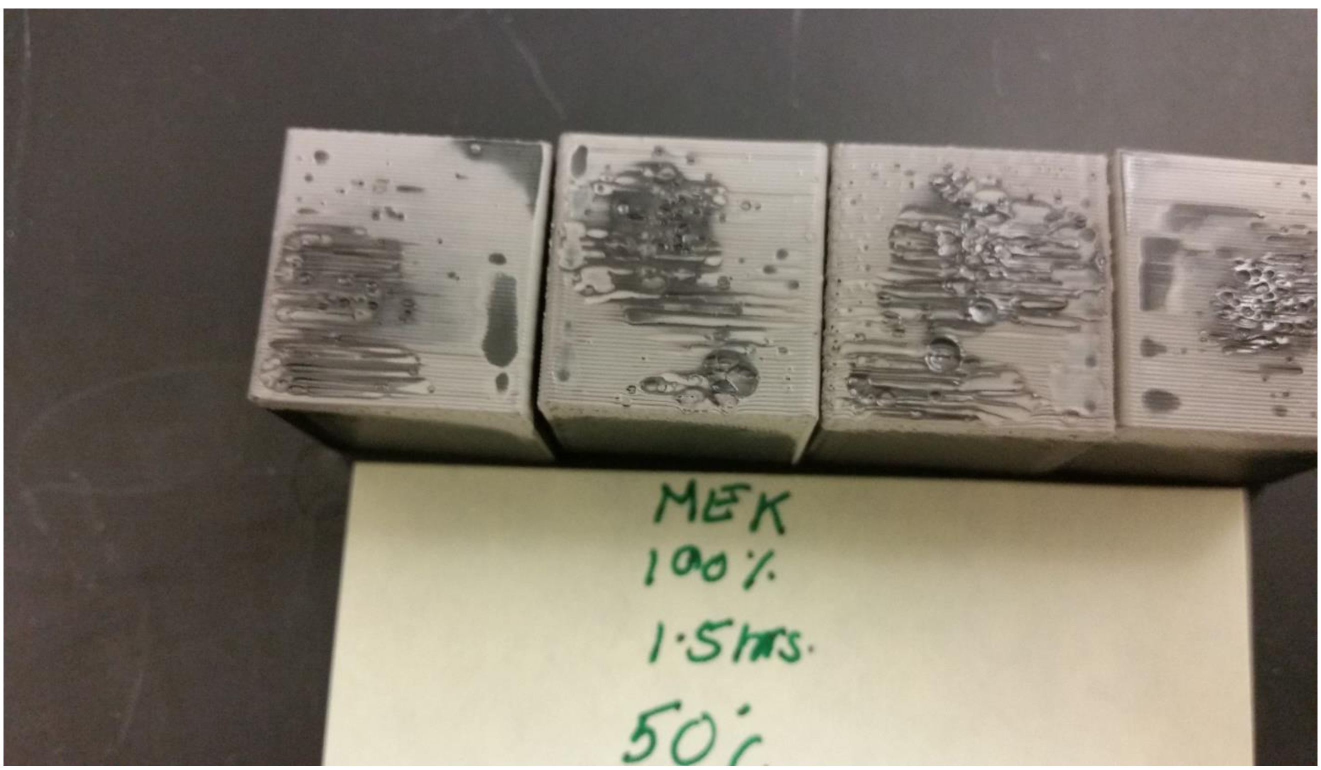


Figure 5.11(a): Optical image of post experiment for Case 10.

Figure 5.11(b): Scanned Images of post treatment from OGP for Case 10.

Table 5.11: Sample surface profile after Case 10.

Sample	Surface profile
Sample 1	0.08369
Sample 2	0.08707
Sample 3	0.02461
Sample 4	0.00585
Sample 5	0.01264

CASE 11:- 100 % concentration, 180 minutes and 50 Celsius

In this case the product is immersed in the 100 percent Methyl Ethyl Ketone solution, for 180 minutes and at the elevated temperature at 50 Celsius. Below are the scanned and optical images of all the images and the final surface profile reading using OGP machine.

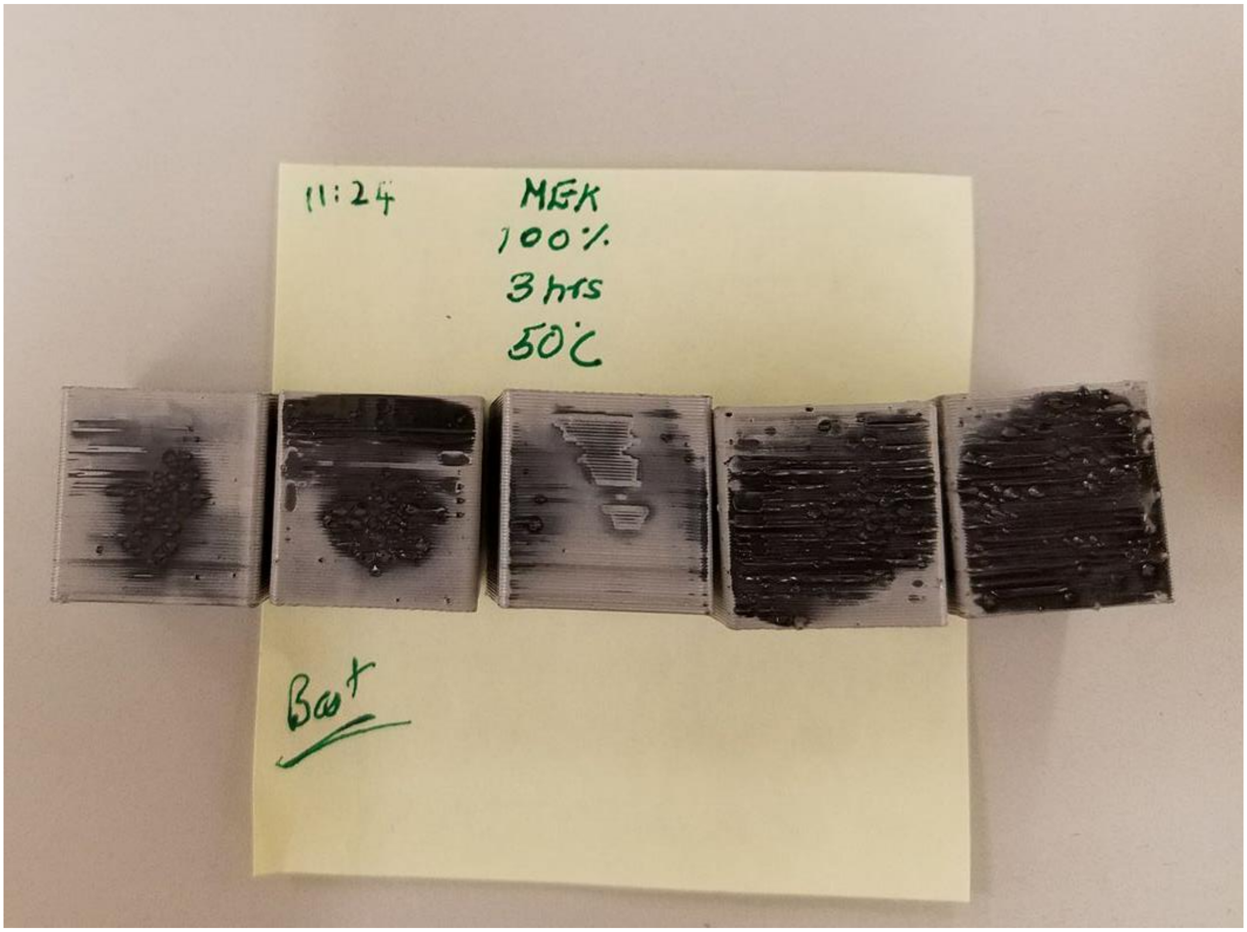


Figure 5.12(a): Optical image of post experiment for Case 11.

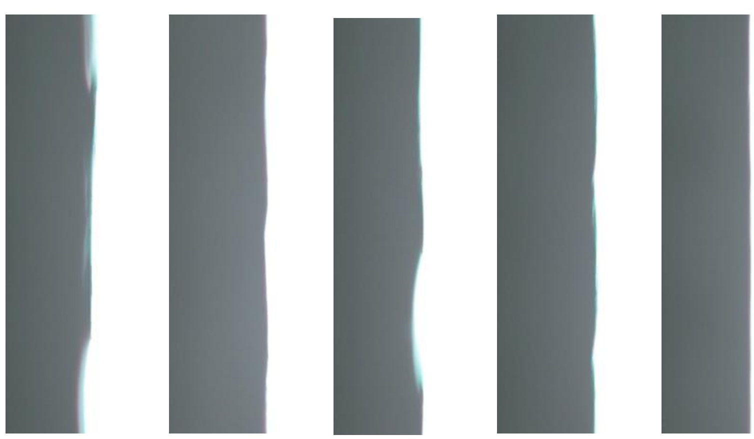


Figure 5.12(b): Scanned Images of post treatment from OGP for Case 11.

Table 5.12: Sample surface profile after Case 11.

Sample	Surface profile
Sample 1	0.01616
Sample 2	0.01650
Sample 3	0.01198
Sample 4	0.02307
Sample 5	0.00211

CASE 12:- 100 % concentration, 360 minutes and 50 Celsius

In this case the product is immersed in the 100 percent Methyl Ethyl Ketone solution, for 360 minutes and at the elevated temperature at 50 Celsius. Below are the scanned and optical images of all the images and the final surface profile reading using OGP machine.

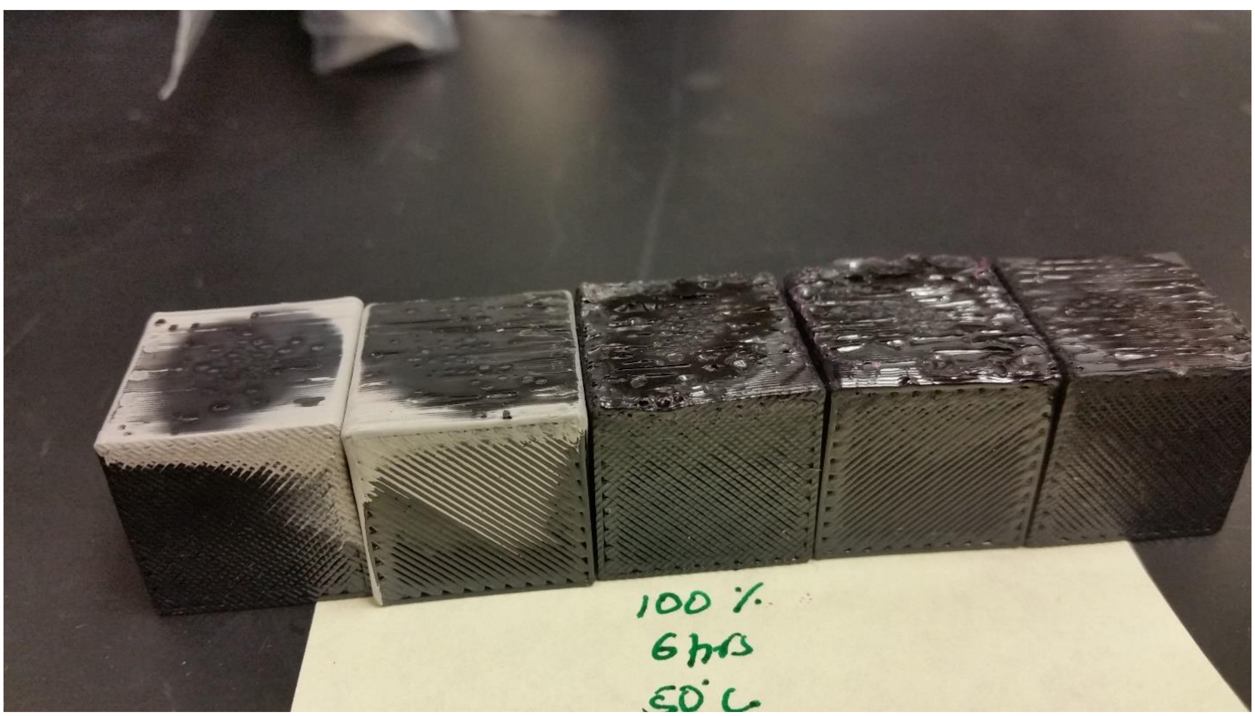


Figure 5.13(a): Optical image of post experiment for Case 12.

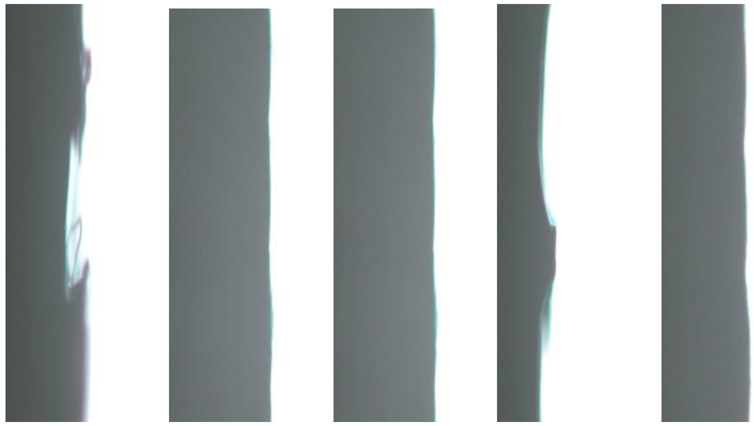


Figure 5.13(b): Scanned Images of post treatment from OGP for Case 12.

Table 5.13: Sample surface profile after Case 12

Sample	Surface profile
Sample 1	0.06383
Sample 2	0.00162
Sample 3	0.03235
Sample 4	0.12759
Sample 5	0.02963

All the parts were taken to the experiments while considering all the parameters at the respected levels. All the products were kept after the experiments for the solution to dry from the surface of the product. As soon as the product is completely dried the product is then taken to the OGP for the final readings.

The sample readings of each product were noted after measuring from the three different parts of a product. The product was measured from both the same side of the edges and from the center side of the product. The middle reading among all the three different readings were considered thus to provide the average reduction on each surface. The product with the average reading was measured and kept along the parts improved with the same parameters. The final

surface profile is then subtracted from the initial recorded surface profile to get the actual surface improved readings are in table 5.15.

Table 5.14: Final surface area measurement.

Sr. No	**Concentration**	**Time**	**Temperature**	**Final Surface Area**
1	90%	90 mins	50 ˚C	400.18
2	90%	180 mins	50 ˚C	412.38
3	90%	360 mins	50 ˚C	399.42
4	90%	90 mins	25 ˚C	402.15
5	90%	180 mins	25 ˚C	403.73
6	90%	360 mins	25 ˚C	401.57
7	100%	90 mins	50 ˚C	399.79
8	100%	180 mins	50 ˚C	398.38
9	100%	360 mins	50 ˚C	399.49
10	100%	90 mins	25 ˚C	402.03
11	100%	180 mins	25 ˚C	403.71
12	100%	360 mins	25 ˚C	403.31

Table 5.15: Final experiment measurement.

Sr. No	Concentration	Time	Temperature	Surface profile	Surface Improved
1	90%	90 mins	50 ˚C	0.09358	0.06565
2	100%	90 mins	25 ˚C	0.00187	0.15736
3	90%	360 mins	50 ˚C	0.05165	0.10758
4	100%	360 mins	50 ˚C	0.06383	0.0954
5	100%	180 mins	25 ˚C	0.00217	0.15706
6	90%	90 mins	25 ˚C	0.00624	0.15299
7	100%	360 mins	50 ˚C	0.00162	0.15761
8	100%	360 mins	25 ˚C	0.00483	0.1544
9	100%	360 mins	25 ˚C	0.00391	0.15532
10	90%	360 mins	50 ˚C	0.03302	0.12621
11	90%	180 mins	25 ˚C	0.01463	0.1446
12	100%	180 mins	50 ˚C	0.01616	0.14307
13	90%	90 mins	25 ˚C	0.00666	0.15257
14	100%	90 mins	25 ˚C	0.13708	0.02215
15	100%	90 mins	50 ˚C	0.08369	0.07554
16	100%	180 mins	50 ˚C	0.01650	0.14273
17	100%	360 mins	25 ˚C	0.00296	0.15627
18	100%	90 mins	50 ˚C	0.08707	0.07216
19	90%	90 mins	50 ˚C	0.12035	0.03888
20	100%	180 mins	50 ˚C	0.01198	0.14725
21	100%	360 mins	50 ˚C	0.03235	0.12688
22	90%	360 mins	50 ˚C	0.01301	0.14622
23	100%	90 mins	50 ˚C	0.02461	0.13462
24	90%	180 mins	25 ˚C	0.00396	0.15527
25	100%	360 mins	50 ˚C	0.12759	0.03164
26	100%	180 mins	25 ˚C	0.00562	0.15361
27	90%	360 mins	25 ˚C	0.01191	0.14732
28	90%	360 mins	25 ˚C	0.02067	0.13856
29	100%	360 mins	50 ˚C	0.02963	0.1296
30	90%	180 mins	50 ˚C	0.00099	0.15824
31	100%	90 mins	25 ˚C	0.00170	0.15753
32	90%	180 mins	25 ˚C	0.00991	0.14932
33	90%	90 mins	50 ˚C	0.10076	0.05847
34	100%	180 mins	50 ˚C	0.02307	0.13616
35	100%	90 mins	25 ˚C	0.00287	0.15636
36	90%	180 mins	25 ˚C	0.01172	0.14751
37	100%	180 mins	25 ˚C	0.01079	0.14844
38	100%	360 mins	25 ˚C	0.00654	0.15269
39	90%	360 mins	50 ˚C	0.12341	0.03582

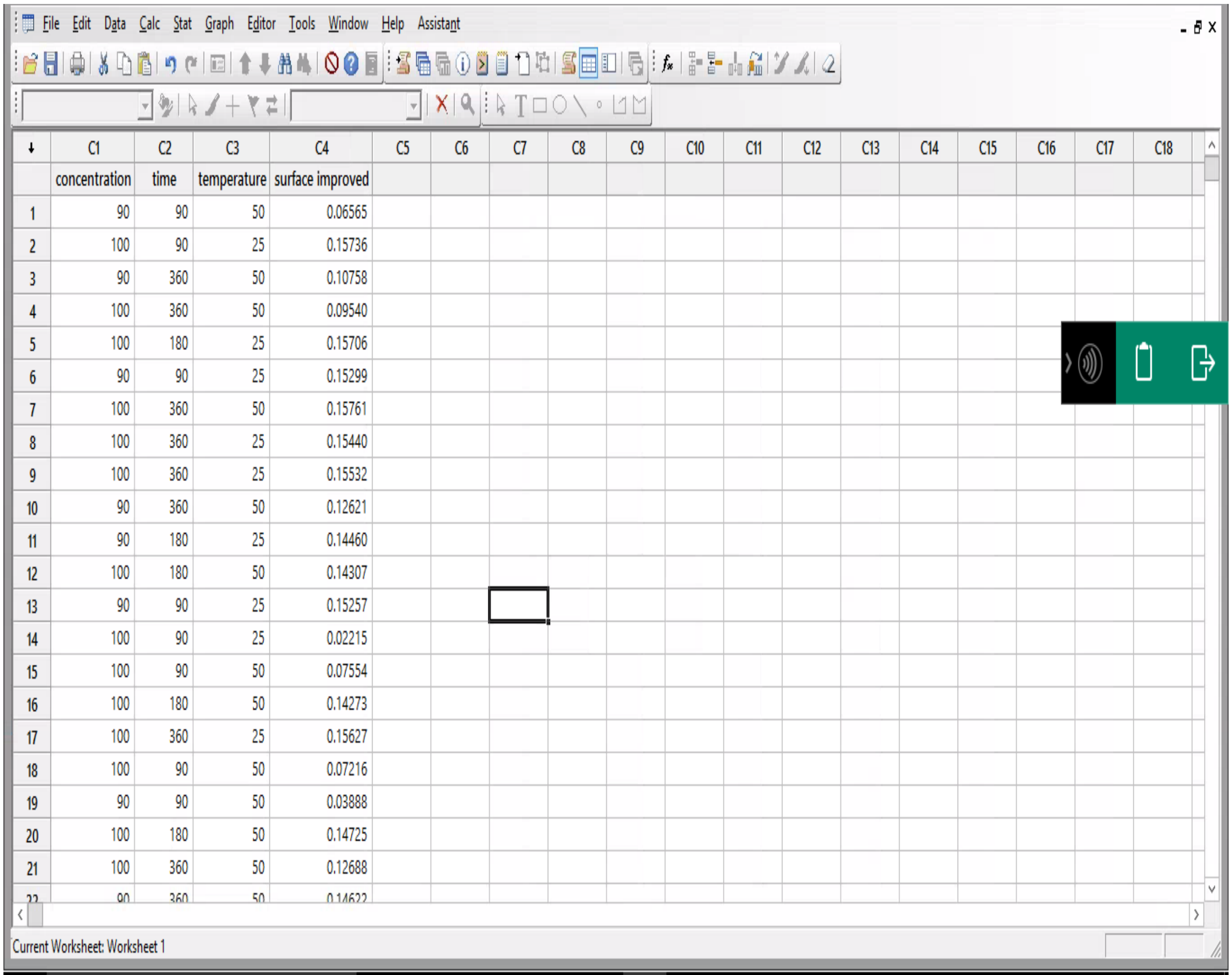
40	90%	180 mins	50 ˚C	0.00546	0.15377
41	90%	180 mins	50 ˚C	0.00127	0.15796
42	100%	180 mins	25 ˚C	0.04349	0.11574
43	100%	90 mins	50 ˚C	0.00585	0.15338
44	90%	90 mins	25 ˚C	0.02035	0.13888
45	100%	180 mins	50 ˚C	0.00211	0.15712
46	90%	90 mins	25 ˚C	0.01529	0.14394
47	100%	180 mins	25 ˚C	0.03553	0.1237
48	90%	360 mins	50 ˚C	0.02761	0.13162
49	90%	360 mins	25 ˚C	0.05715	0.10208
50	100%	90 mins	50 ˚C	0.01264	0.14659
51	90%	360 mins	25 ˚C	0.00686	0.15237
52	90%	180 mins	50 ˚C	0.01011	0.14912
53	90%	90 mins	25 ˚C	0.00337	0.15586
54	100%	90 mins	25 ˚C	0.00241	0.15682
55	90%	90 mins	50 ˚C	0.10597	0.05326
56	90%	180 mins	50 ˚C	0.00150	0.15773
57	90%	180 mins	25 ˚C	0.00468	0.15455
58	90%	90 mins	50 ˚C	0.00726	0.15197
59	90%	360 mins	25 ˚C	0.00152	0.15771
60	100%	360 mins	25 ˚C	0.00516	0.15407

The part is immersed in the Methyl Ethyl Ketone solution with the varying parameters and their respected levels. The part is then measured for the initial surface roughness with the 403.31 mm square. The part is immersed in the solution and the change was measured using the Vernier caliper to measure the length and the breadth of the product later the surface area was calculated. The change was clearly measured at the elevated temperatures.

5.3 DESIGN OF EXPERIMENTS ANALYSIS

Experiments were performed as per the combinations of parameters and in order as displayed in the table above and the results for the surface roughness value were recorded. Five readings were recorded on product with the same environment conditions. Further, using MINITAB software these readings were analyzed to obtain the optimum condition. The Data Means and S-N ratio plot for main effects and interaction plots are shown below. The data acquired while performing the experiment was solved using Data Means Plot and S-N Ratio plot. The condition was taken for the S-N ratio was larger is better. Results obtained from the Data Means

and the S-N Ratio give the same optimized condition. ANOVA is used to find the significant factor in the experiment.



	C1	C2	C3	C4
	concentration	time	temperature	surface improved
1	90	90	50	0.06565
2	100	90	25	0.15736
3	90	360	50	0.10758
4	100	360	50	0.09540
5	100	180	25	0.15706
6	90	90	25	0.15299
7	100	360	50	0.15761
8	100	360	25	0.15440
9	100	360	25	0.15532
10	90	360	50	0.12621
11	90	180	25	0.14460
12	100	180	50	0.14307
13	90	90	25	0.15257
14	100	90	25	0.02215
15	100	90	50	0.07554
16	100	180	50	0.14273
17	100	360	25	0.15627
18	100	90	50	0.07216
19	90	90	50	0.03888
20	100	180	50	0.14725
21	100	360	50	0.12688

Figure 5.14: Data is entered in MINITAB for ANOVA.

In ANOVA the data is to be arranged in a manner that we have each factors in one different column and the response in one separate column. The first three columns here represent three different factors concentration, time and temperature. The fourth column represent the surface improved of a product when it is applied to the respective factors.

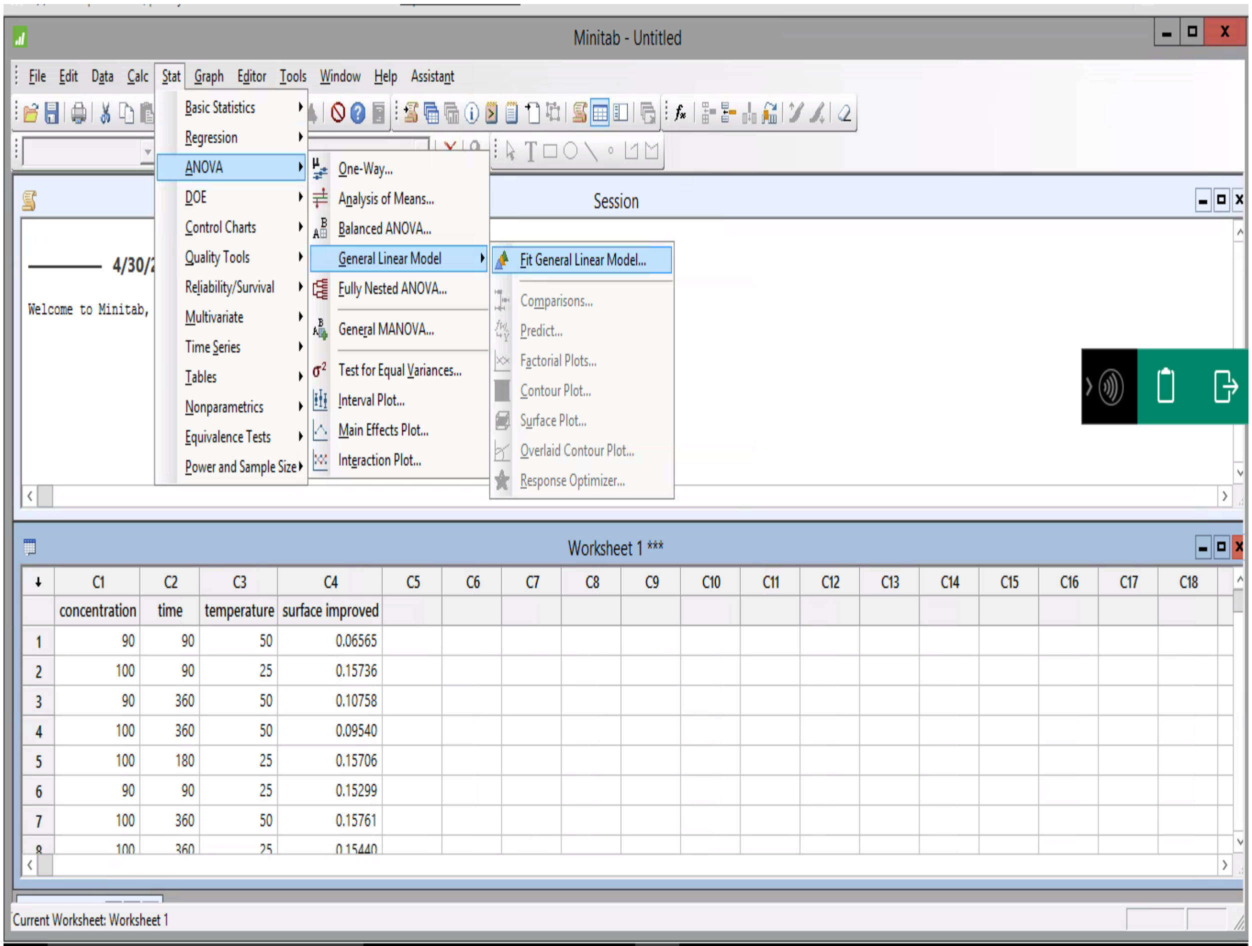


Figure 5.15: Process to reach GLM in ANOVA.

After the Data is entered in MINITAB the Statistic tab is selected from the top bar in the MINITAB in which ANOVA (Analysis of Variance) is selected to find the significant factor while performing the experiments. From the ANOVA General Linear Model is selected after that Fit General Linear Model is selected to reach to the process in this balanced data is provided. In a GLM procedure there is one response required and one or more factors are required, fixed factors are applied in this case. In the GLM tab that pops out in response bar surface improved is selected and below it is factors tab where concentration, time and temperature is selected. At the bottom there are many tabs provided among which model tab is selected to add the interactions as a factor among all the main selected factors.

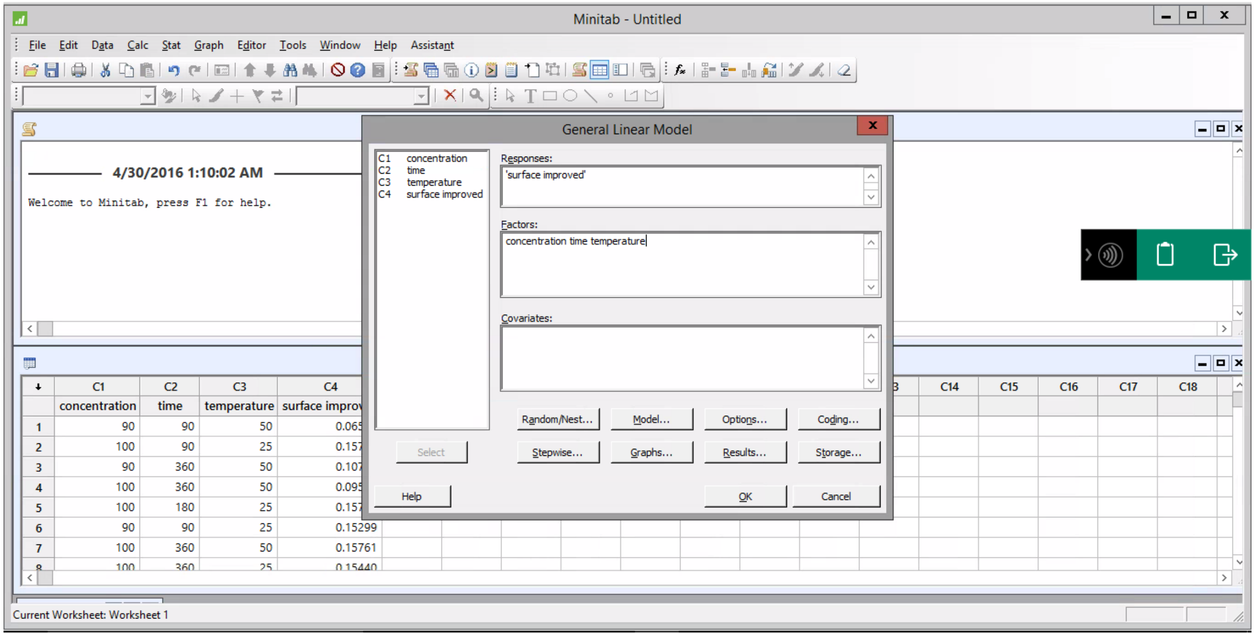


Figure 5.16: General linear model.

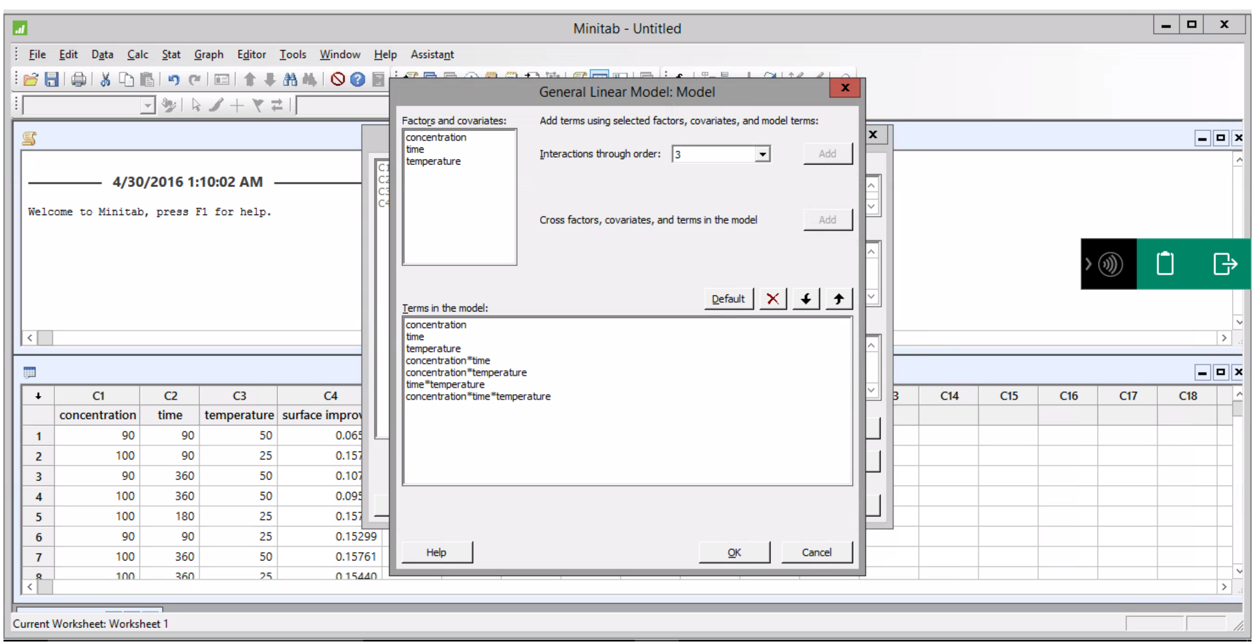


Figure 5.17: Interactions addition in factors to measure their contribution.

Factor Information

Factor	Type	Levels	Values
conc	Fixed	2	90, 100
time	Fixed	3	90, 180, 360
temp	Fixed	2	25, 50

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
conc	1	0.000121	0.000121	0.12	0.734
time	2	0.009508	0.004754	4.60	0.015
temp	1	0.009954	0.009954	9.63	0.003
conc*time	2	0.001366	0.000683	0.66	0.521
conc*temp	1	0.000876	0.000876	0.85	0.362
time*temp	2	0.007347	0.003674	3.55	0.036
conc*time*temp	2	0.004198	0.002099	2.03	0.142
Error	48	0.049622	0.001034		
Total	59	0.082992			

Figure 5.18: ANOVA results.

ANOVA is used to find the significant factors in improving the surface finish among all the factors and their interactions. The confidence level was set up to 95% which implies that the factors that have their P-value less than 0.05 are the significant factors. The results obtained from the ANOVA determines time, temperature and the interaction between time and temperature as the factors which played the major role in improving the surface finish. These factors were chosen as all the factors have their P-value less than the 0.05 value, thus making the note of the significant factors so that more focus can be kept on them.

Taguchi Method

This methodology is focused on improving the quality of a product by analyzing the variation without eliminating the causes. This approach was based on conventional statistical tools together with some guidelines in order to design experiments and analyzing the results of these experiments. Taguchi design is used to analyze how, control factors, noise factors and signal factors that affect the response. The data is entered in the different format for taguchi design.

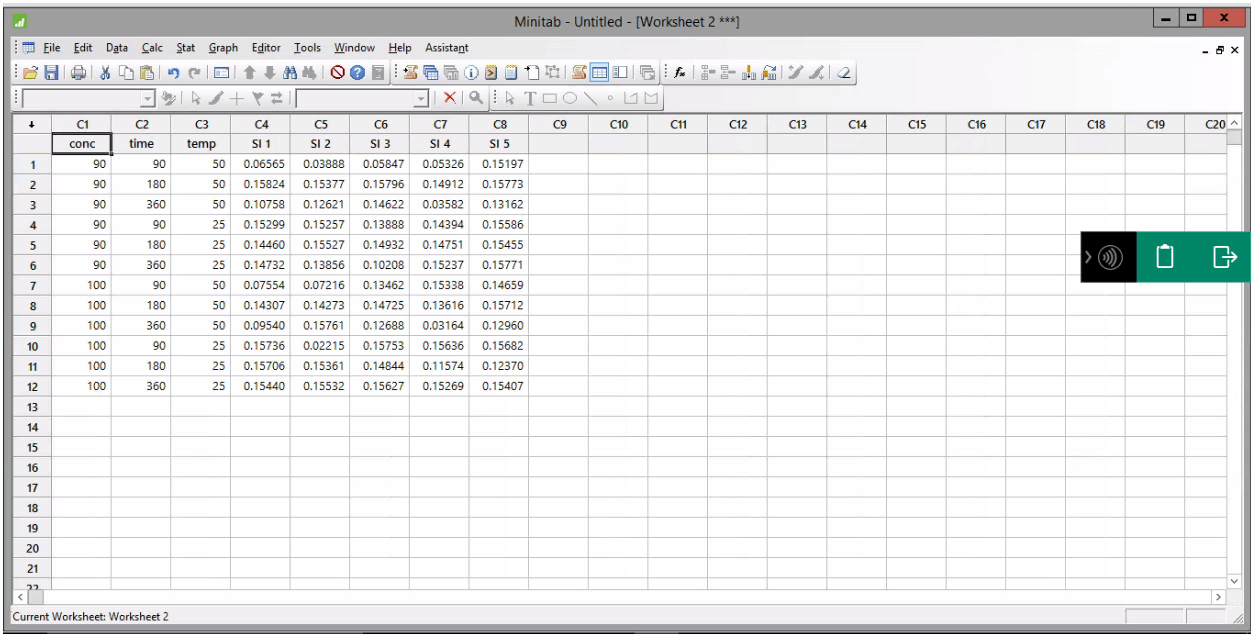


Figure 5.19: Data entered in MINITAB for taguchi design.

The data that is entered first in the format required for Taguchi design. The factors for the experiment are defined by clicking on Define Custom Taguchi Design. In the factor tab add the factors add concentration, time and temperature factor.

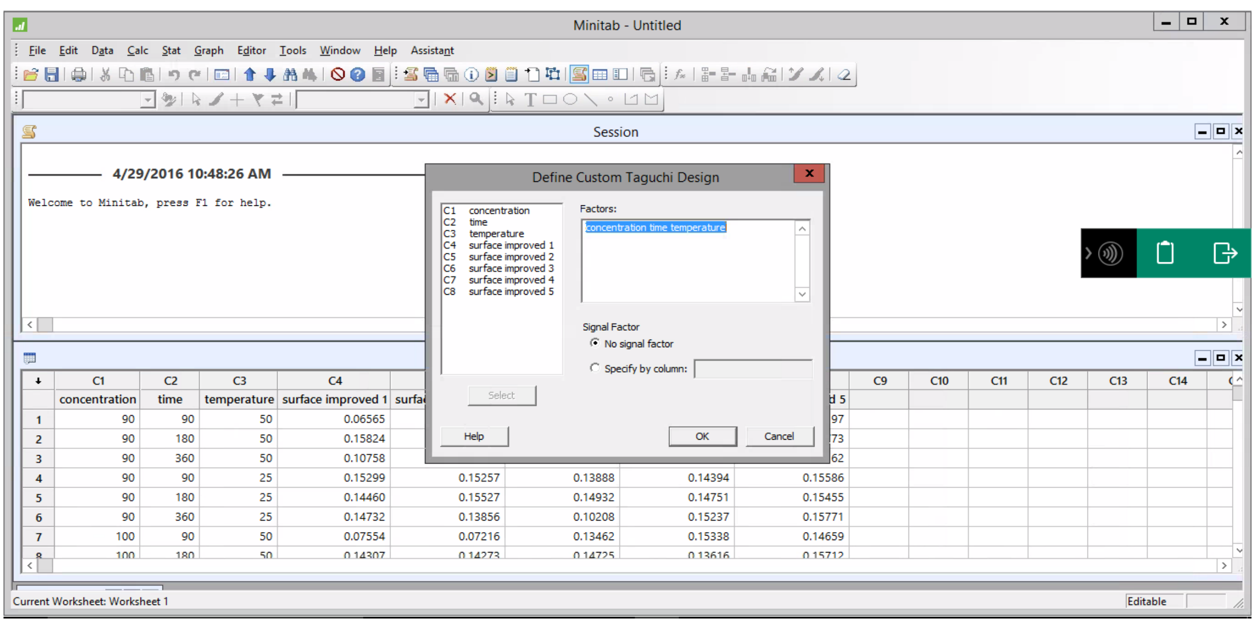


Figure 5.20: Define taguchi design.

Analyze the Taguchi Design is done after the data is defined in taguchi tab. When Analyze the Taguchi Design tab is selected to analyze the result of robust parameter design experiment using an orthogonal array. As Analyze Taguchi Design is selected there are tab opened in which there is the response bar add all the responses obtained from the experiment as shown below in figure 34. There are many small tabs below in the main window of Analyze the Taguchi design open all the tabs and select the options as shown below in figure 35, 36 and 37. In graphs tab the option are selected to find the data for main factors, interaction factors, means and find the signal to noise ratios. In the terms tab select all the available terms which played the role in improving the surface roughness. In the options tab Larger the better option is chosen because the greater the surface roughness value is desired therefore this option is selected.

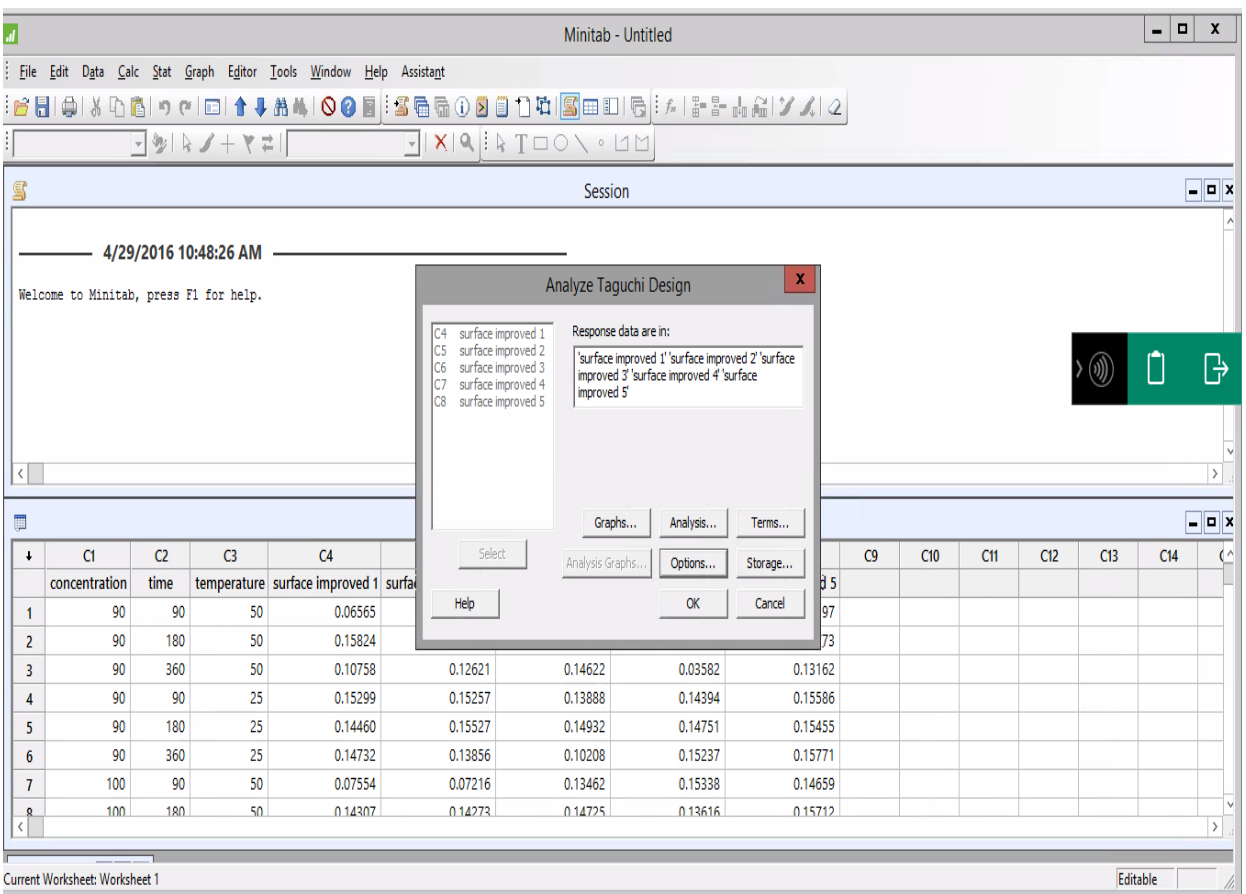


Figure 5.21: Analyze taguchi design

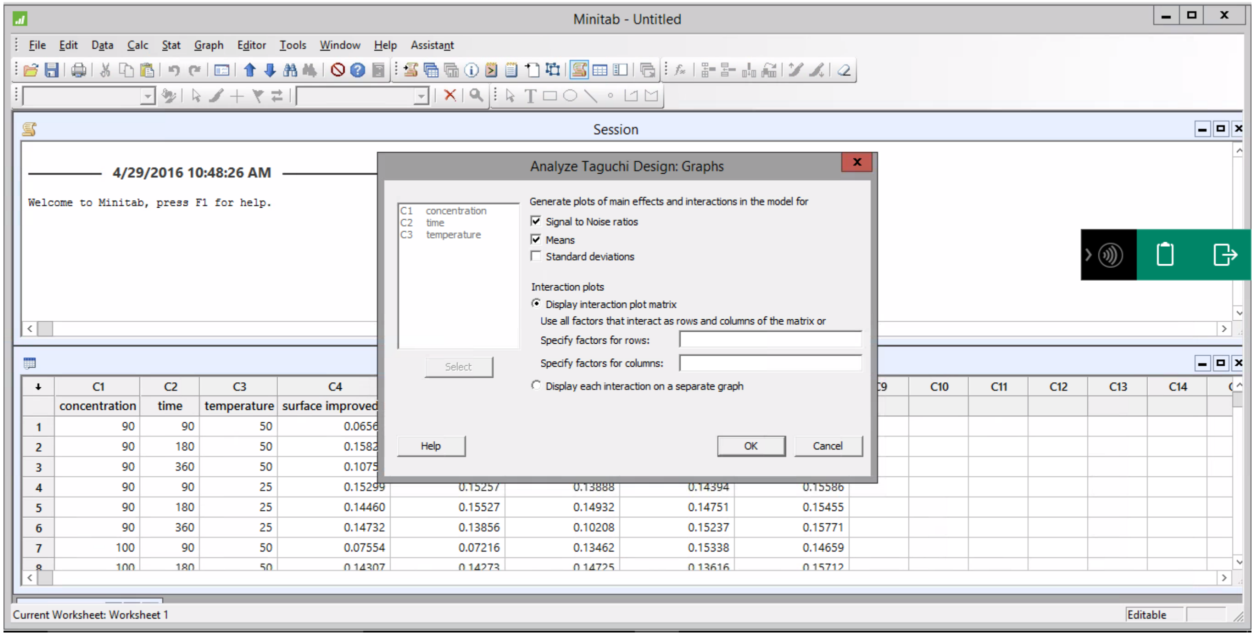


Figure 5.22: Analyze taguchi design graphs tab.

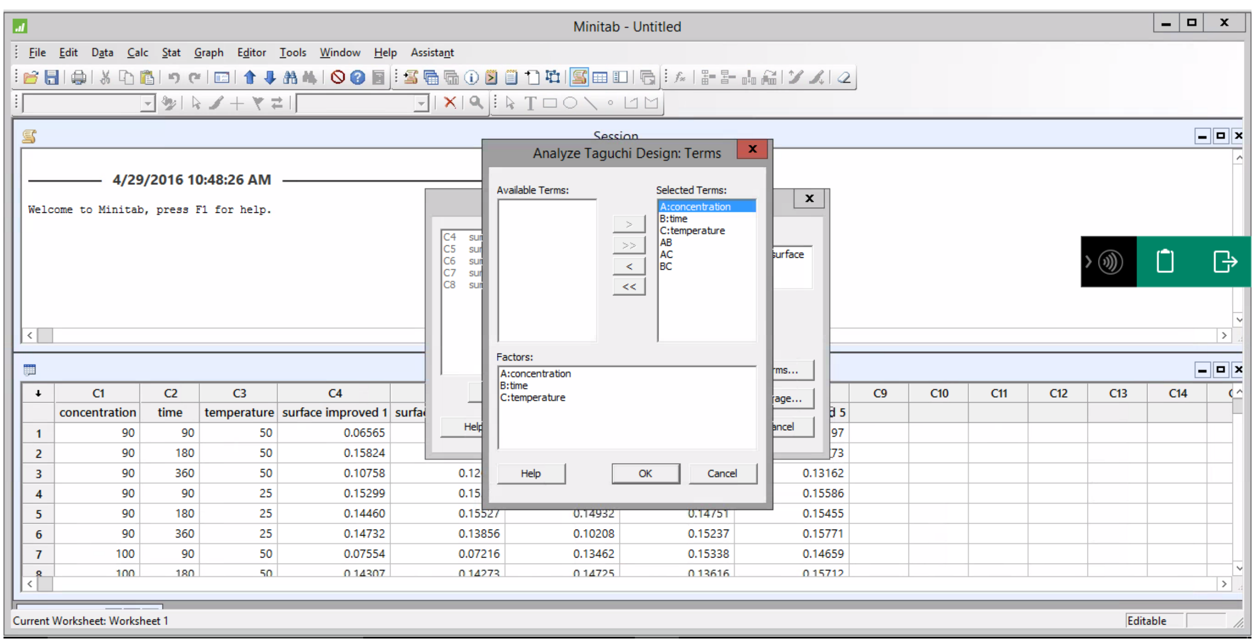


Figure 5.23: Analyze taguchi design terms tab.

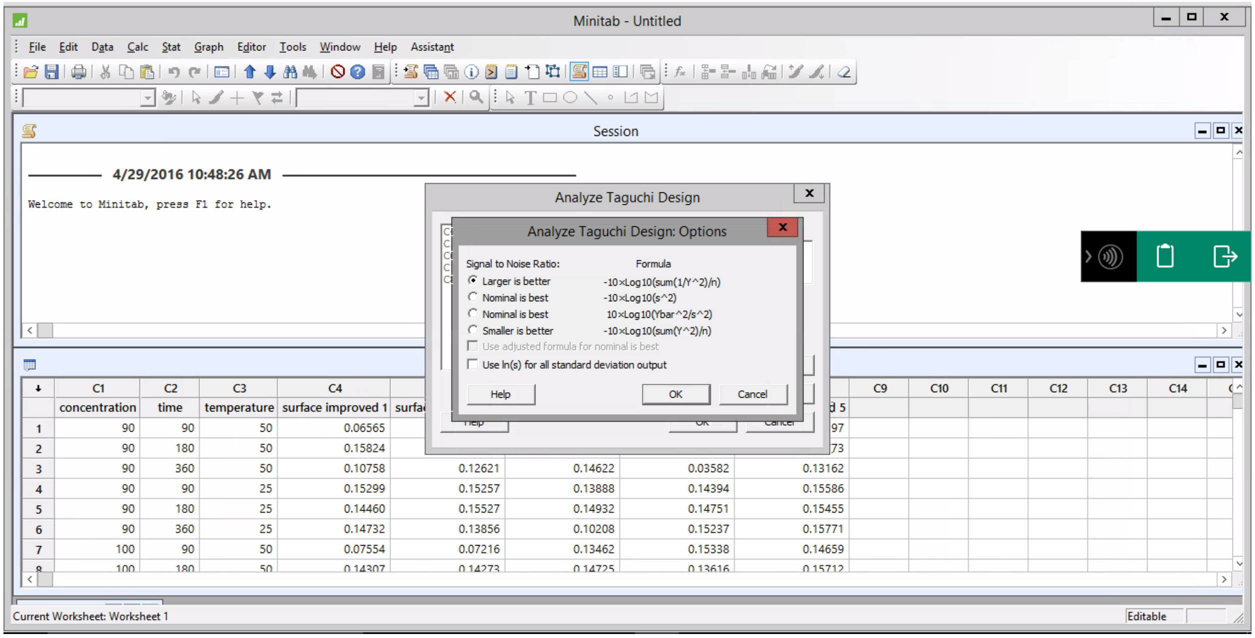


Figure 5.24: Analyze taguchi design options tab.

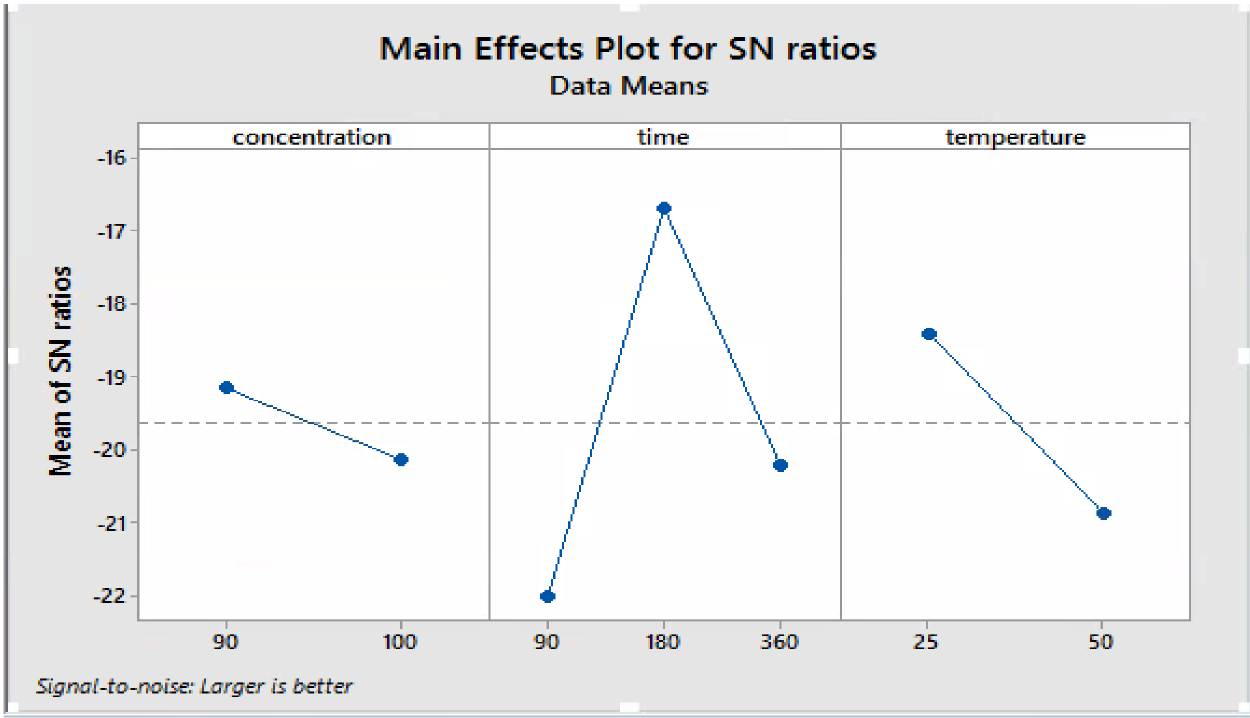


Figure 5.25: Main effects plot for SN ratios.

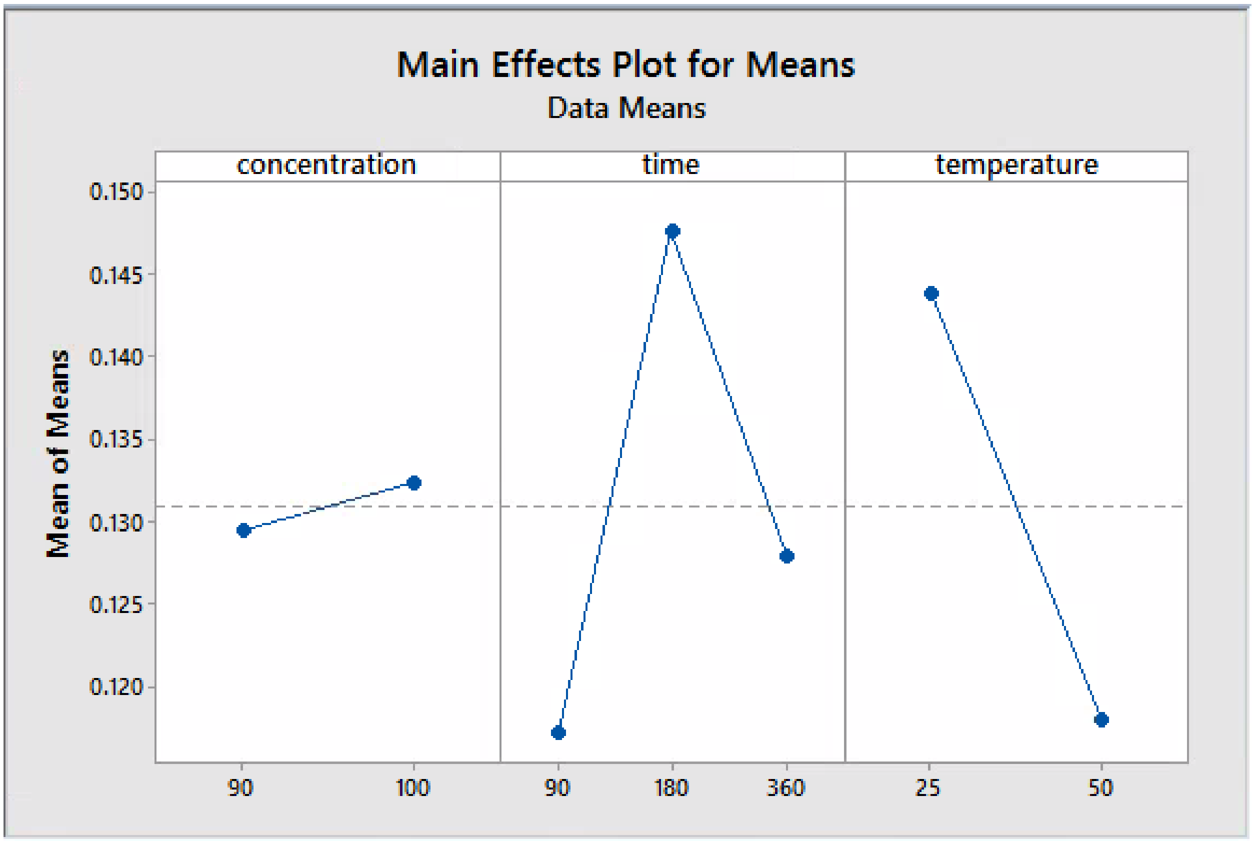


Figure 5.26: Main effects plot for means.

In the Main effects plot it is clearly visible that how much every factor affects the response characteristics. A main effect is seen when different level of factor affect the characteristic in a different manner. When there are two factors it is easily visible that one level of factor increases the mean compared to another level. The difference that is caused between the two levels is called the main effect. By comparing the slopes of the lines the relative magnitude of the factor effects can be compared. Characteristic average for each factor and each of their level are taken from the responses with respect to all factors at their levels. Interaction plot is drawn to see the factor is improving the surface roughness on own or it needs the support from the other factors. If there are two factors with two levels then there are four points plotted on the graph and the different levels of same factor are connected to each other. If those two lines are parallel to each other than two

factors don't interact to each other but if they cross each other than interactions also play a role in performing the experiment.

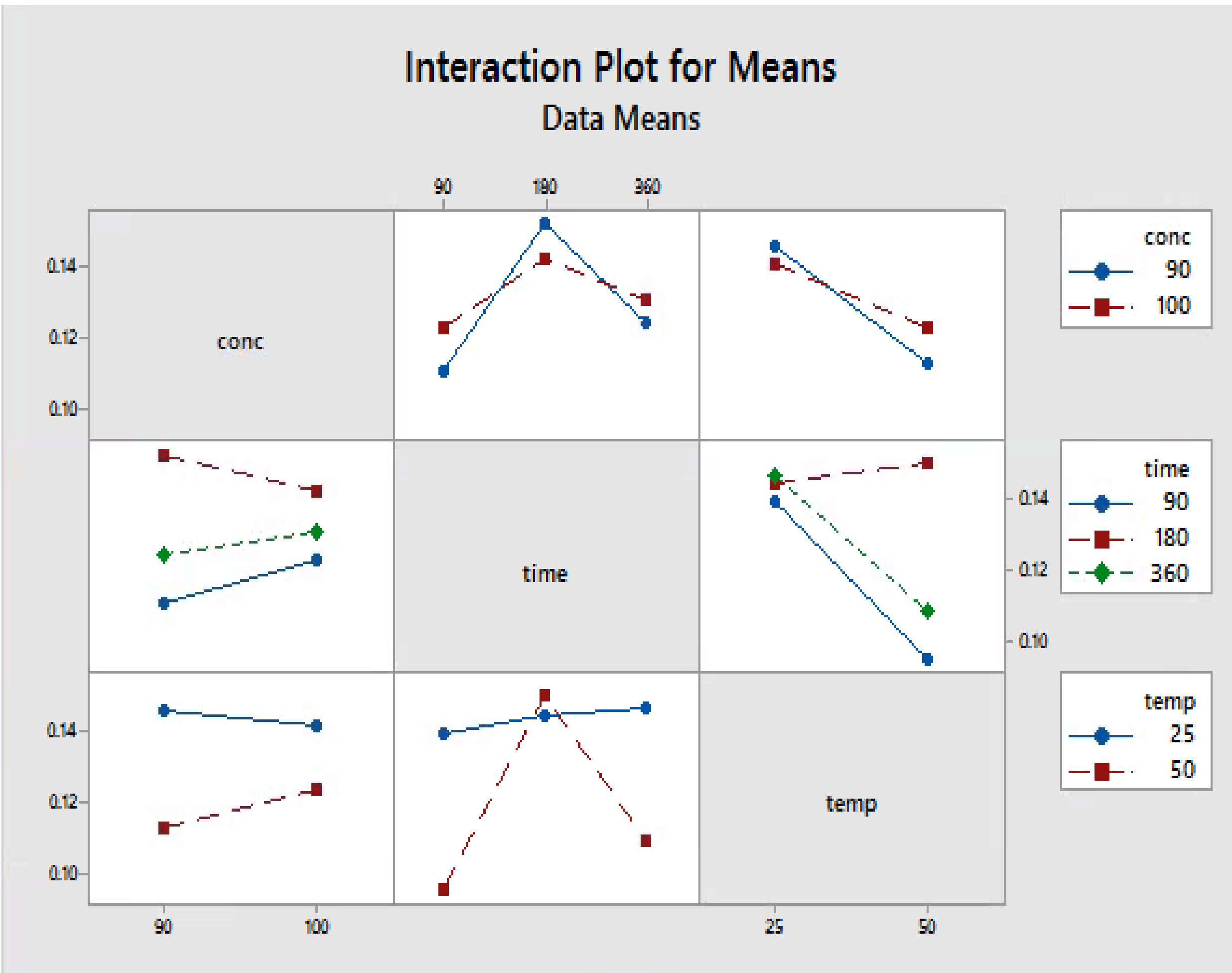


Figure 5.27: Interaction plot for means

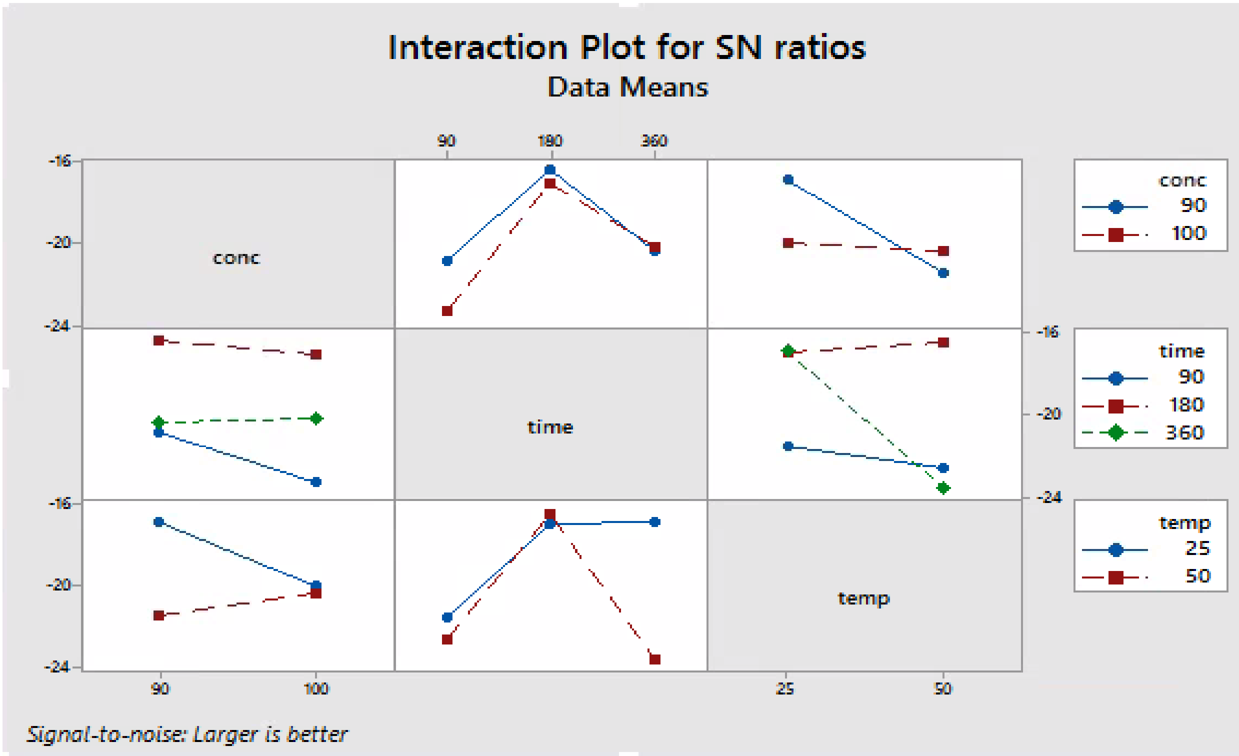


Figure 5.28: Interaction plot for SN ratios.

Response Table for Signal to Noise Ratios
Larger is better

Level	concentration	time	temperature
1	-19.14	-22.03	-18.41
2	-20.15	-16.68	-20.88
3		-20.22	
Delta	1.01	5.34	2.47
Rank	3	1	2

Response Table for Means

Level	concentration	time	temperature
1	0.1295	0.1172	0.1438
2	0.1324	0.1476	0.1181
3		0.1280	
Delta	0.0028	0.0304	0.0258
Rank	3	1	2

Figure 5.29: Result obtained from taguchi design.

The contribution of the factor are according to the ranks in the above tables, Time, temperature and concentration for the mean and the S/N ratio. The best operating conditions are concentration 90, time 180 and temperature 25. The results obtained from the ANOVA and obtained from the Taguchi design are interrelated both of them showed time and temperature as important factors and concentration as the third predicted factor.

Chapter 6: Results and Conclusion

6.1 Results

All the samples from the Case 1 to Case 12 have experienced reduction in roughness value after the ULTEM 9085 part was immersed in Methyl Ethyl Ketone with keeping the different factors at different levels. The readings obtained are then analyzed on the DOE and ANOVA using MINITAB software. The contribution of the factor are accordingly, Time, temperature and then concentration for the mean and the S/N ratio. There was improvement noticed on every part but along with them best operating conditions are concentration 90, time 180 and temperature 25. The results obtained from the ANOVA and obtained from the Taguchi design are as time and temperature as significant factors. There were many two and three order interaction factors which contributed in improving the surface roughness among all of them interaction factor between time and temperature played the important role in improving the surface roughness. The solution with higher concentration showed some defects at higher concentration and at the elevated temperature.

6.2 Conclusion

In this research the surface roughness of the ULTEM 9085 is addressed with MEK with all the different parameters and their levels. Parameters that have significant effect on the surface roughness value in the chemical treatment process have been identified. The post chemical treatment method was optimized in terms of time of exposure of solution to part, temperature of the solution and the concentration of the chemical bath using Design of Experiments and ANOVA. The significant factors are time, temperature and the interaction of the time and temperature. The optimum condition which was analyzed using DOE and ANOVA is 90 percent concentration, for 180 minutes at the 25 Celsius.

6.3 FUTURE WORK

The Optimum condition in improving the surface roughness and even the significant factor in improving surface roughness for ULTEM 9085 has been identified. The experiments were performed on the simple parts it will be a great research in finding the optimum condition and significant factors for the complex parts of ULTEM 9085. In this results were recorded with the OGP, the results with it gives the approximate readings for the accurate readings the experiment readings can be noted down with the help of Profilometer or SEM.

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Appendix

Abbreviations

RP:- Rapid Prototyping

FDM:- Fused Deposition Modelling

SLA:- Stereo Lithography Apparatus

3-D:- Three Dimensional

STL:- Stereo Lithography file format

ABS:- Acrylonitrile Butadiene Styrene

FST:- Flame Smoke and Toxicity Rating

DOE:- Design Of Experiments

MEK:-Methyl Ethyl Ketone

ANOVA:- Analysis of Variance

CAD:- Computer Aided Design

S/N:- Signal to Noise Ratio

OA:- Orthogonal Array

LM:- Layered Manufacturing

CMM:- Co-ordinate Measuring Machine

Vita

Saurabh Rakesh Nayyar was born in Nagpur, India. He received his bachelor of technology in Mechanical Engineering from Rashtrasanth Tukadoji Maharaj Nagar University (RTMNU), Nagpur, India in the year 2014. In August 2014, he joined the department of Industrial, Manufacturing and Systems Engineering (IMSE) to pursue Master of Science Degree in Industrial Engineering. In March 2016 he started his research career as a Graduate Research Assistant (GRA) under the supervision of Dr. Bill Tseng. Dr. Bill Tseng and Dr. Amit Lopes guided him throughout his research period. Before starting this research, he had a limited knowledge of 3-D Printing. However, during this research he gained good research skill and knowledge on 3-D Printing.

Mr. Nayyar is a student member of INCOSE since 2015. The research which he led as a GRA motivated him towards the completion of M.S.I.E. He would like to express his utmost gratitude to UTEP for providing an admirable education, knowledge and research opportunity while pursuing his M.S.I.E degree. Furthermore, he would like to convey a sincere appreciation to his thesis advisor Dr. Bill Tseng, for mentoring him towards the completion of the M.S.I.E thesis entitled,

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