# Micro Electropolishing of the MEMS Metallic Structures Fabricated by the Micro WEDM Process

**Mohammad Tahmasebipour ***
Faculty of New sciences and Technologies,
University of Tehran, Tehran, 14395 -1561, Iran
Micro/Nanofabrication Technologies Lab, Faculty of New Sciences and Technologies,
University of Tehran, Tehran, 14395 -1561, Iran
E-mail: tahmasebipour@ut.ac.ir
*Corresponding author

**Younes Tahmasebipour**
Micro/Nanofabrication Technologies Lab, Faculty of New Sciences and Technologies,
University of Tehran, Tehran, 14395 -1561, Iran
E-mail: tahmasebipour@gmail.com

**Mahya Boujari Aliabadi, Shadi Ebrahimi**
Faculty of New sciences and Technologies,
University of Tehran, Tehran, 14395 -1561, Iran
Micro/Nanofabrication Technologies Lab, Faculty of New Sciences and Technologies,
University of Tehran, Tehran, 14395 -1561, Iran
E-mail: boujari.mahya89@gmail.com, E-mail: shadibrhm1994@gmail.com

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**Abstract:** In this study, the micro electro-polishing method was employed to improve the surface quality of microbeams machined by the micro WEDM method and to remove the recast layer. This approach changes the dimensions of the microbeams, as a result of the electrochemical corrosion, in addition to the elimination of the recast layer. To diminish the impact of this process on the dimensional deviation of the fabricated microbeams, the influence of the micro electro-polishing process parameters such as voltage, duration, cathode diameter, and electrolyte composition on the dimensional deviation of microbeams was studied using the Taguchi method. The optimum values of process parameters were determined by the S/N ratios analysis, and the order of parameters importance was determined through analysis of variance of the S/N ratios. It was found that the optimal levels of the process parameters are voltage of 2 V, process duration of 20 s, cathode diameter of 50 mm, and electrolyte composition of 25-5-40 ml (sulfuric-phosphoric-water) within the range of experiments. By using the optimum values of the parameters, the dimensional deviations were found to be 5.23 times lower compared to the average of the results. The importance of process parameters was found to follow this order: electropolishing duration, electrolyte composition, cathode diameter, and process voltage.

**Keywords:** Microelectromechanical Systems, MEMS, Micro Wedm, Micro Polishing, Micro Electropolishing, Wire Electrical Discharge Machining,

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**Biographical notes: Mohammad Tahmasebipour** is an associate professor in the Faculty of New Science and Technologies at University of Tehran, Iran. He received his PhD in Mechanical Engineering from Tarbiat Modarres University, Iran, in 2009. **Younes Tahmasebipour** received his MSc degree in Mechanical Engineering from the Khaje Nasir Toosi University of Technology, Iran, in 2011. **Mahya Boujari Aliabadi** received her MSc in Micro-Nanoelectromechanical systems from University of Tehran, Iran, in 2018. **Shadi Ebrahimi** received her MSc in Micro-Nanoelectromechanical systems from University of Tehran, Iran, in 2022.

Research paper

## 1 INTRODUCTION

Microelectromechanical Systems (MEMS) have a wide range of applications in various industries. Conventional methods for the fabrication of MEMS are very efficient for the mass production of simple two-dimensional geometries; however, they are very complex and time-consuming for three-dimensional systems. Micro electrical discharge machining (micro EDM) and microwire electrical discharge machining (micro WEDM) processes have been quite effective in facing such challenges. The micro EDM and WEDM processes that offer low-energy electrical discharges and small tool sizes, as in the range of micrometers [1] and nanometers [2-6], can be employed for machining very complex silicon geometries. In the manufacturing process of a gyroscope, a cavity is used as a mold to produce a thin-walled diamond hemisphere, which is the main component of the gyroscope. To build an accurate small-scale gyroscope, a combination of EDM and chemical etching processes was applied by Fonda et al. [7-8]. Given the excellent anodic bonding properties of borosilicate glass and its flawless surface, it is usually used as the substrate in MEMS.

In these systems, several micro-holes are often created on the substrate to get electrical contacts. Creating micro-holes with a diameter of fewer than 200 µm is difficult using traditional machining methods. A hybrid method of electrical discharge micromachining and ultrasonic micromachining was used to address this problem by Yan et al. [9]. Dry electrical discharge micromachining with reverse polarity was employed for machining large amounts of pure carbon nanotubes that are used as cathode in electrochemical processes by Saleh et al. [10]. The EDM process can be used in the fabrication of micro tools for replication of micro polymer components that are widely applied in MEMS, micro opto-electro-mechanical systems, micro bio-electromechanical systems, and microfluidic systems [11]. Silicon carbide is an advanced ceramic with many industrial applications. Given its low fracture toughness, it is difficult to cut SiC using conventional machining methods.

In addition, the increasing tendency toward miniaturization in MEMS and the semiconductor industry has made it necessary to develop micromachining techniques for advanced ceramics. In recent years, researchers have managed to successfully machine SiC using the EDM process [12]. A comparison of surface quality and dimensional accuracy of the micro gears fabricated using the micro EDM and micro WEDM processes was conducted by Ali et al. [13]. They showed that the surface quality and dimensional accuracy in the micro WEDM process are significantly better. Due to their advantages, MEMS accelerometers have found widespread applications in different fields. Two novel capacitive MEMS accelerometers made of steel fabricated using the micro WEDM method have been introduced by Tahmasebipour et al. [14-15] for the first time. These MEMS accelerometers provide better control over noise reduction and damping, withstand high-amplitude accelerations, and their dynamic range has considerably improved in comparison to the conventional MEMS accelerometers.

Piezoelectric motors are extensively used in precise positioning systems. Fabrication of a novel one-axis inchworm piezo-motor and a novel high-performance integrated two-axis inchworm piezo-motor using micro WEDM process was reported by Tahmasebipour et al. [16-17]. Micro-scale natural convection plays an important role in heat transfer in microelectronic components and MEMS. The micro WEDM process was used to fabricate an array of micro fined copper heat sinks with a great heat transfer ratio by Mahmoud et al. [18].

Today, microelectromechanical grippers have found many applications in the manipulation of micro and nano-components and systems. Fabrication of a novel microgripper using the micro WEDM process was reported by Mohd Zubir et al. [19]. Nowadays, MEMS-based fuse devices are of great interest. Previous studies were mainly directed toward reducing the cost and size of fuse devices. Through the application of WEDM and UV-LIGA in the production of MEMS-based fuse devices, Du et al. [20] reduced the production cost and time. The reverse micro WEDM technique was used by Liao et al. [21] to fabricate high aspect ratio metal microarrays. The WEDM process was employed to fabricate metallic microcantilevers by Mancang et al. [22]. They investigated the effect of the process parameters on the surface finish of the micro-cantilevers. Fabrication of high aspect ratio metallic and ceramic complex micrometer parts using micro WEDM process was reported by Schoth et al. [23].

Optimization of the dimensional deviation resulted from the micro WEDM process in the MEMS structures machining has been reported by Tahmasebipour et al. [24]. In the micro EDM/WEDM process, a recast layer remains on the machined surfaces which are associated with high residual stresses, micro-cracks, and carbide structures. Therefore, it is necessary to remove the recast layer and improve the surface texture before the part can be used. The recast layer characteristics and surface integrity of SiC/Al particulate MMC in the micro WEDM process were investigated by Zhenlong et al. [25]. Also, the effect of the microwire electrical discharge machining process parameters on the recast layer was investigated by Tahmasebipour et al. [26]. Despite the use of micro WEDM processes in the fabrication of the MEMS, no research has addressed the removal of the recast layer in this process. In the EDM process, the heat generated by electrical discharges is the main factor. Therefore, this process is defined as a thermal process as the intense heat applied to a small area of the workpiece results in local melting and vaporization of the melted material. It is observed that only a small percentage of the melted material is washed by the dielectric, and the rest remain as a recast layer on the machined surface.

This layer has high residual stress and incorporates a network of cracks and microcracks. Therefore, the recast layer must be removed and the surface is to be improved before the device can be used. Various methods are used for surface polishing, including mechanical and electropolishing. Given that the MEMS are composed of very small components in the range of microns, applying mechanical force to the systems leads to plastic deformation or even failure in their structures. Therefore, the use of mechanical polishing methods for removing the recast layer in MEMS is not advised. Also, mechanical polishing applies high strain on the surface, and the surface becomes effectively exposed to external work, severely damaging the surface crystals, and significantly altering the mechanical properties of the surface.

On the other hand, electropolishing does not inflict such changes as in electrochemical processes. In mechanical polishing, surfaces are exposed to a high temperature. This often leads to localized thermal expansion and, thereby, distortion in the parts, especially in thin parts. Cleaning the surface free of foreign particles such as abrasives that penetrate the structure surface during the mechanical polishing is very difficult and maybe impossible even by washing repeatedly. On the other hand, electropolishing not only removes all the previous contaminations from the surface but also results in great resistance to the adhesion of contaminants in the environment due to its excellent surface smoothness. Therefore, the micro electro-polishing process is recommended for removing the recast layer and improving the surface of MEMS components fabricated by the micro EDM and WEDM processes.

In this study, to improve the surface quality of the microbeams machined by the micro WEDM and to remove the residual recast layer, the microbeams surface was polished using the micro electropolishing process. To reduce the dimensional deviation of the fabricated microbeams, the effects of micro electropolishing process parameters such as voltage, time, cathode diameter, and electrolyte composition on the dimensional deviation of microbeams were studied using the Taguchi method. By setting the parameters to the optimum values, the dimensional deviation was found to be 5.23 times lower compared to the average test results.

## 2 MATERIALS AND METHODS

### 2.1. Micro Electropolishing System

The most practical way to remove the recast layer from the surface of the MEMS components fabricated by the micro WEDM process is micro electro-polishing. Generally, electro-polishing involves an anode, cathode, electrolyte, and the potential difference between the anode and the cathode. In this study, a system was designed and manufactured for micro electro-polishing the MEMS components fabricated by the micro EDM/WEDM processes. In this configuration, the MEMS components (i.e. microbeams) act as the anode, while a stainless-steel bushing functions as the cathode, and a solution of sulfuric acid and phosphoric acid in deionized water is the electrolyte, and a DC voltage source was used to create a potential difference between the anode and the cathode. A schematic form of the micro electro-polishing system is shown in “Fig. 1”.

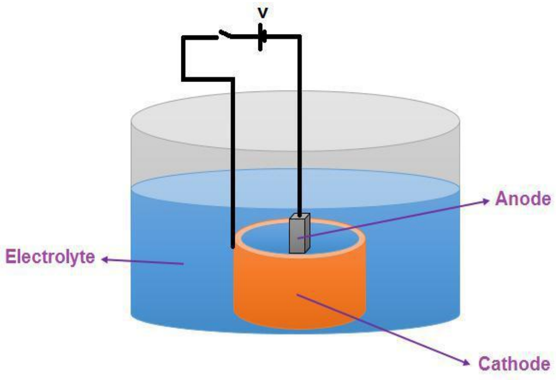

**Fig. 1** Schematic form of micro electropolishing system.

### 2.2. Optimization of Micro Electropolishing Process

Application of the micro electropolishing process to remove the residual recast layer from the micro WEDM process on the microbeams not only removes the recast layer but also results in the corrosion of the microbeams as well in dimensional changes. The aim of micro electropolishing process optimization is to minimize the dimensional deviation of the microbeams polished using this method. The effect of different parameters in the micro electropolishing process on the microbeam dimensional deviation was studied using the Taguchi method. This method is an effective tool to reduce the number of the required experiments in processes optimization [27-30]. Application of the Taguchi method in optimizing the micro electropolishing process consists of the following steps:

Step 1. Defining the main function: In this study, the microbeam dimensional deviation (the microbeam size difference before and after the micro polishing process) was defined as the main function of the micro electropolishing process.

Step 2. Defining process parameters and the corresponding levels: Parameters involved in the micro electropolishing process include voltage, micro electropolishing duration, cathode diameter, and composition of the electrolyte solution. The range of these parameters was defined based on initial experiments as follows:

1. Micro electropolishing voltage (v): the applied voltage in the process of micro electropolishing is one of the main factors determining the process rate. In the 1.5-2.25 volts range, the micro electropolishing process creates a smooth and bright surface. Therefore, the effect of this voltage range was investigated.
2. Micro electropolishing duration (t): This parameter determines the duration that microbeams are polished using the micro electropolishing process. The process duration greatly affects the amount of corrosion and the surface finish. The range of these parameters was considered 20 to 80 seconds based on the preliminary experiments.
3. Cathode diameter (D): In this study, a stainless-steel bushing was used as the cathode. The farther anode is from the cathode, the lower is the rate of electrochemical corrosion. Therefore, to evaluate the effect of distance between the cathode and the workpiece, bushings with diameters of 30, 40, 50, and 60 mm were used.
4. Electrolyte composition ($E_C$): The electrolyte solution used in the micro electropolishing process is an acid composition diluted with water. In this study, a solution of sulfuric acid and 85% orthophosphoric in water was used. The combination of these acids with water decreases its corrosiveness and makes it more controllable. In this study, 25 to 100 ml of an electrolyte solution of sulfuric acid and 5 to 20 ml orthophosphoric acid (85%) in 40 ml of DI water were used. For these four parameters in the selected ranges, four levels were defined as shown in “Table 1”.

Step 3. An $L_{16}$ orthogonal array was selected for the micro electropolishing process optimization.

**Table 1** Micro electropolishing process parameters and defined levels

| Parameter | | Level | | | | Unit |
|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | |
| V | Process voltage | 1.5 | 1.75 | 2 | 2.25 | V |
| t | Process duration | 20 | 40 | 60 | 80 | S |
| D | Cathode diameter | 30 | 40 | 50 | 60 | mm |
| $E_C$ | Sulfuric-Phosphoric-water | 25-5-40 | 50-10-40 | 75-15-40 | 100-20-40 | mL |

## 3 RESULTS AND DISCUSSION

The configuration of the micro electropolishing experiments, based on the selected orthogonal array, is given in “Table 2”. The SEM (Scanning Electron Microscope) images of the microbeams before and after the micro electropolishing with a magnification of 350 are shown in “Fig. 2” (there is some contamination on the microbeams surface that is removed by the polishing process) and “Fig. 3”, respectively. To determine the microbeam's dimensional deviation, the microbeam size difference before and after the polishing process was calculated. The results are shown in “Table 2”.

**Table 2** Configuration of the micro electropolishing experiments using orthogonal array $L_{16}$.

| Expt. No. | Parameters & levels | | | | Dimensional deviation (μm) | S/N (dB) |
|---|---|---|---|---|---|---|
| | V | t | D | $E_C$ | | |
| 1 | 1 | 1 | 1 | 1 | 3.2 | -10.1030 |
| 2 | 1 | 2 | 2 | 2 | 4 | -12.0412 |
| 3 | 1 | 3 | 3 | 3 | 5 | -13.9794 |
| 4 | 1 | 4 | 4 | 4 | 8.5 | -18.5884 |
| 5 | 2 | 1 | 2 | 4 | 6 | -15.5630 |
| 6 | 2 | 2 | 1 | 3 | 5.9 | -15.417 |
| 7 | 2 | 3 | 4 | 2 | 4 | -12.0412 |
| 8 | 2 | 4 | 3 | 1 | 9 | -19.0849 |
| 9 | 3 | 1 | 3 | 2 | 1.5 | -3.5283 |
| 10 | 3 | 2 | 4 | 1 | 6.3 | -15.9868 |
| 11 | 3 | 3 | 1 | 4 | 4.1 | -12.2557 |
| 12 | 3 | 4 | 2 | 3 | 8 | -16.2583 |
| 13 | 4 | 1 | 4 | 3 | 4.5 | -13.0643 |
| 14 | 4 | 2 | 3 | 4 | 1.7 | -4.6089 |
| 15 | 4 | 3 | 2 | 1 | 6.5 | -15.2583 |
| 16 | 4 | 4 | 1 | 2 | 5.5 | -14.7083 |

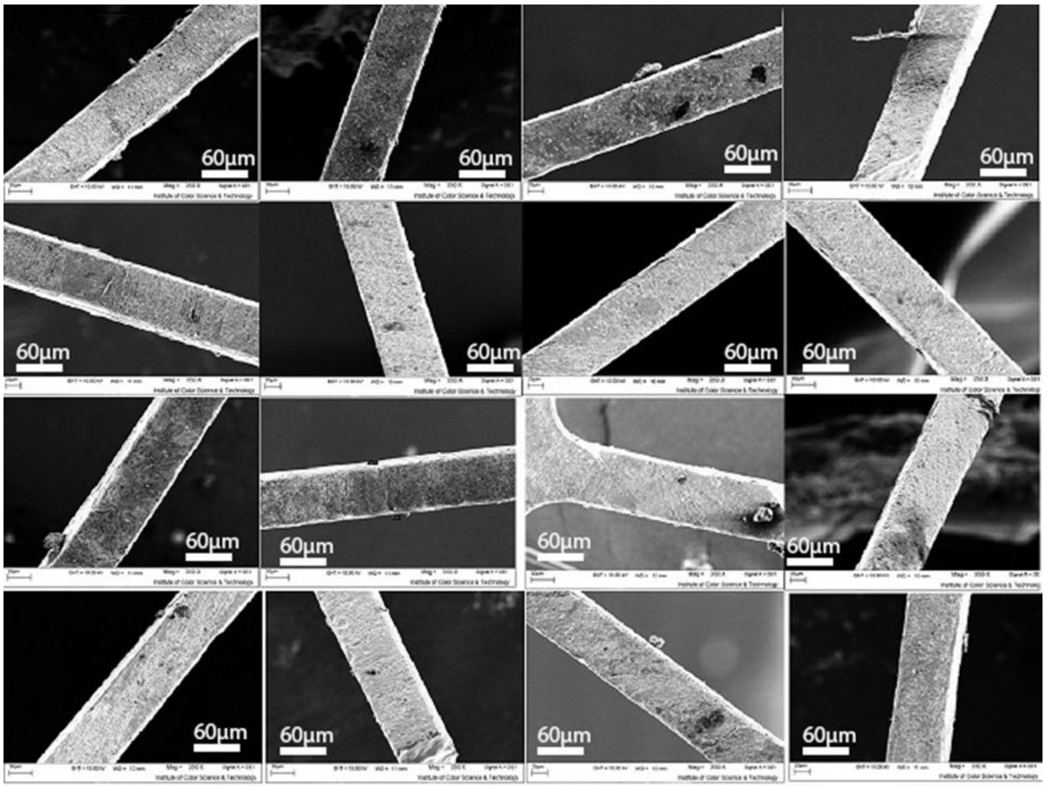

**Fig. 2** SEM image of the microbeams before micro electropolishing (from left to right and top to down according to the number of the experiment in Table 2, respectively).

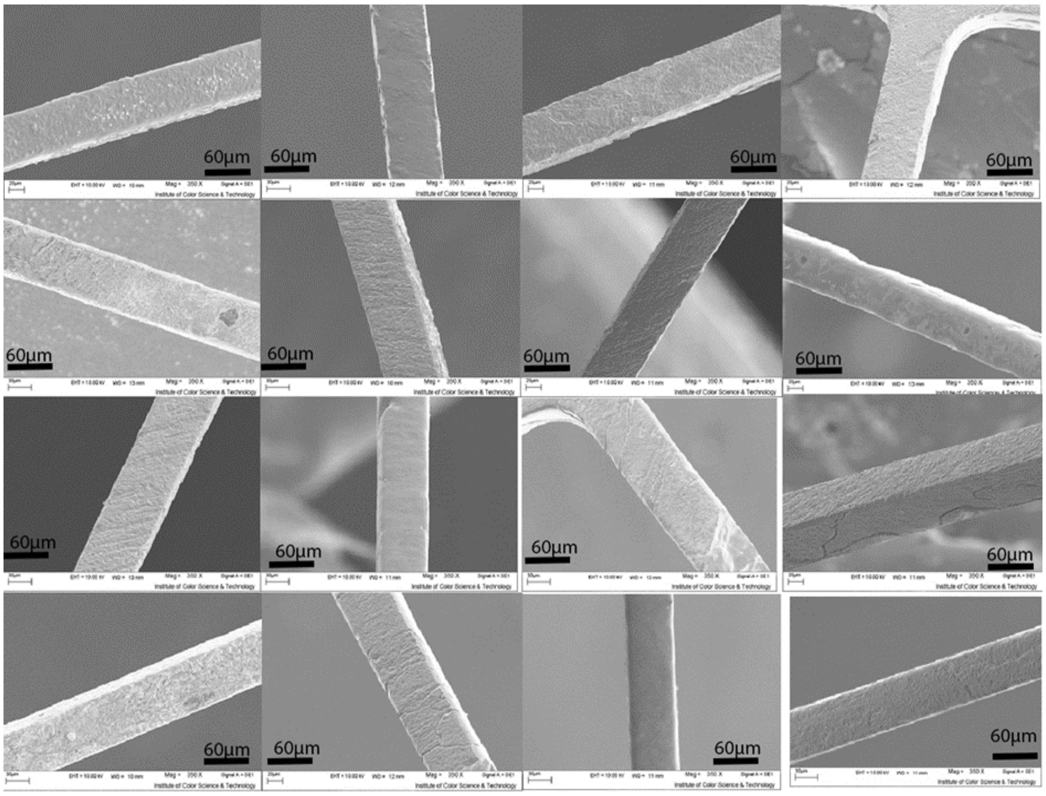

**Fig. 3** SEM image of the microbeams after micro electropolishing (from left to right and top to down according to the number of the experiment in Table 2, respectively).

### 3.1. Analysis of the S/N Ratios

In this study, based on the Taguchi method, the minimum dimensional deviation of the microbeam (lower is better, LB) is defined as the better performance of the process. For LB, the S/N ratio is calculated using “Eq. (1)”:

$$\eta = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} L_i^{2}\right) \qquad (1)$$

The S/N ratios for the $L_{16}$ experiments have been calculated by the Minitab 16 software and are shown in “Table 2”. The S/N ratios mentioned in the table can be used to calculate the mean S/N ratios at different levels of each process parameter using “Eq. (2)”:

$$\bar{\eta} = \left(\frac{1}{m}\sum_{k=1}^{m}\eta_{ijk}\right) \qquad (2)$$

The results of the calculation of mean S/N ratios at different levels of process parameters are shown in “Table 3”, and the diagram showing the effects of different levels of process parameters on the S/N ratio is shown in “Fig. 4”.

**Table 3** Average values of the S/N ratios at different levels of the process parameter

| S/N (dB)<br>Level | V | t | D | $E_C$ |
|---|---|---|---|---|
| 1 | -13.678 | -8.895 | -13.146 | -10.753 |
| 2 | -15.513 | -12.014 | -14.85 | -14.11 |
| 3 | -12.00 | -13.63 | -10.30 | -14.925 |
| 4 | -12.185 | -17.18 | -14.92 | -13.446 |

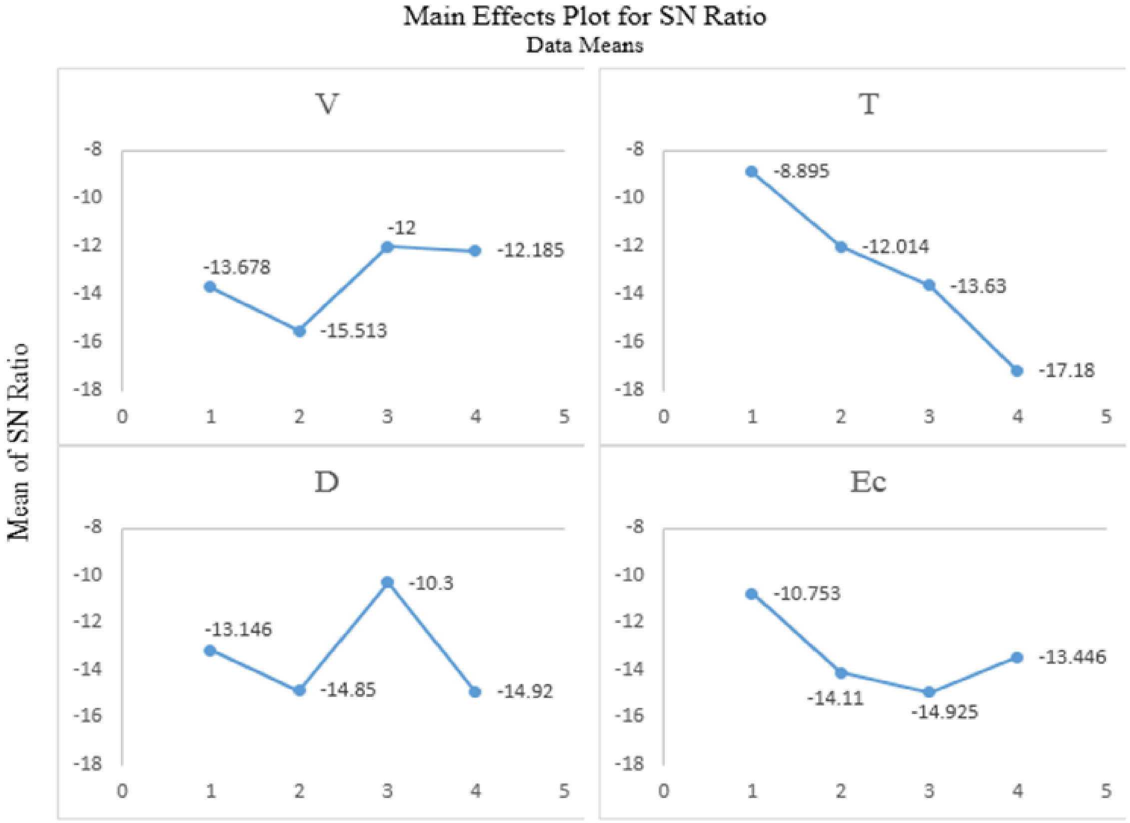

**Fig. 4** Effect of micro electropolishing process parameter on the S/N ratio.

The results presented in “Table 3” and “Fig. 4” suggest:

1) Process Voltage (v): The maximum S/N ratio corresponds to the level 3 voltage (2 Volts); therefore, the dimensional deviation of the electropolished microbeams at this voltage level is minimum.

2) Micro electropolishing duration (t): Higher micro electropolishing duration increases electrochemical polishing. The S/N ratio is maximum at level 1 of this parameter (20 s). Therefore, at this level of micro electropolishing duration, the dimensional deviation of the microbeams is minimum due to a low amount of corrosion.

3) Cathode diameter (D): It is observed that the maximum S/N ratio corresponds to level 3 of cathode diameter (50 mm); therefore, the dimensional deviation of the electropolished microbeams is minimum at this level.

4) Electrolyte composition ($E_C$): The diagram that corresponds to the electrolyte composition shows the effect of acids used in the process on the dimensional deviation of micro electropolished microbeams. It is observed that the dimensional deviation is optimum at level 1 of this parameter.

Considering the descriptions above, the optimal levels of the parameters in the micro electropolishing process for achieving the lowest dimensional deviation in the micro electropolished microbeams are as follows: the voltage at level 3 (2 V), electro-polishing duration at level 1 (20 s), cathode diameter at level 3 (50 mm), and the electrolyte composition at level 1 (25-5-40 ml).

### 3.2. Analysis of Variance of the S/N Ratios

The relative importance of micro electropolishing process parameters in the dimensional deviation of the microbeams was determined using the analysis of variance (ANOVA) of S/N ratios. The results of the ANOVA of the S/N ratios are presented in "Table 4". According to the table, the higher the F ratio and the distribution percentage of a parameter, the higher its impact on the dimensional deviation of the microbeams. Therefore, the order of process parameters' importance on the dimensional deviation of the microbeams was found to be: electropolishing duration, electrolyte composition, cathode diameter, and voltage. Micro electropolishing duration indicates the time duration that microbeams are polished. Therefore, the further the process duration the further amount of corrosion and the dimensional deviation. But, the process voltage range is inherently very limited (1.5 - 2.25 volts). Consequently, the voltage has less impact on the dimensional deviation.

### 3.3. Confirmation Experiment

The final step in the Taguchi method is to evaluate the performance of the studied process using the optimal levels of the parameters. To conduct the confirmation experiment, micro electropolishing process parameters were set at the optimal level, and a microbeam that was machined using the micro WEDM was polished by the micro electropolishing method. Figure 5 shows the SEM image of the microbeam before and after micro electropolishing at 500x magnification. The dimensional deviation obtained from this experiment was about 1 µm. It is evident that dimensional deviation is about 5.23 times lower than the average of the results of the experiments when setting the micro electropolishing process parameters at the optimal level. Moreover, the S/N ratio was improved by 13.185 dB.

**Table 4** Analysis of variance of S/N ratio

| Source | Degree of freedom ( f ) | Sum of squares ( S ) | Variance (V) = ( S/f ) | F-Ratio = ( $V/V_{error}$ ) | Distribution percentage P (%) = ( $S/S_{total}$ ) * 100 |
|---|---|---|---|---|---|
| v | 3 | 39.78 | 13.26 | 1.5 | 14.30 |
| t | 3 | 111.51 | 37.17 | 4.158 | 40 |
| D | 3 | 47.87 | 15.96 | 1.785 | 17.163 |
| $E_C$ | 3 | 52.93 | 17.65 | 1.98 | 18.98 |
| Error | 3 | 26.81 | 8.94 | | 9.56 |
| Total | 15 | 278.9 | | | 100 |

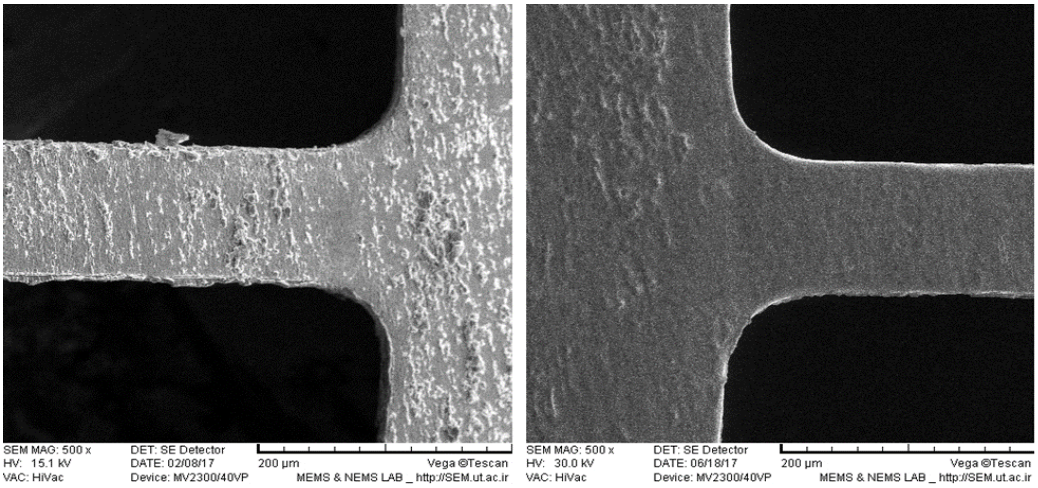

**Fig. 5** SEM image of the microbeam before (left) and after (right) micro electropolishing at 500x magnification.

## 4 CONCLUSION

In this research, micro electropolishing was employed to improve the surface quality of the microbeams fabricated by the micro WEDM process and to remove the recast layer from their surfaces. To optimize the dimensional deviation of the micro beams in the micro electropolishing process, the effect of the process parameters including voltage, duration, cathode diameter, and electrolyte composition was studied using the Taguchi method. The optimum values of the process parameters were determined by the S/N ratios analysis, and the order of parameter importance was determined through analysis of variance of the S/N ratios. It was found that the optimal levels of the process parameters are voltage of 2 V, process duration of 20 s, cathode diameter of 50 mm, and electrolyte composition of 25-5-40 ml (sulfuric-phosphoric-water) within the range of experiments. By setting the parameters to the optimum values, the dimensional deviation was found to be 5.23 times lower compared to the average test results. The importance of process parameters was found to follow this order: electropolishing duration, electrolyte composition, cathode diameter, and process voltage.

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