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Artificial Neural Networks for the Prediction of Electrochemical Etched Micro Channel Dimensions

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Abstract: In this study, an artificial neural network was used to model the size of the microchannel in a specific pattern created with the electrochemical etching method. Special Series 5754 aluminum plates were coated with employing masks. The pre-designed pattern was then marked to the masked surface with a laser, then it was subjected to the electrochemical etching process. In this way, micro-patterned channels are formed on the aluminum surface. Various experiments were carried out based on the electrochemical etching parameters, such as concentration (0.1-2.5 M), the distance between the electrodes (5-15 cm), operating voltage (15-48 V), and time (6-30 min). And the depth and width of the channels were investigated. Studies conducted under various conditions were modeled with ANN and the synergistic effects of the input and output parameters were explored by the surface graphics obtained as a result of the modeling. This modeling study is a powerful tool in terms of providing a prediction of the channel dimensions of the microchannel fabricated by electrochemical etching for future related studies. In addition to the modeling, some impressions and inferences obtained from the experiments were also given in the conclusion part.

Keywords: Electrochemical etching, Microchannel, Modelling, Artificial neural network

Elektrokimyasal Olarak Aşındırılmış Mikro Kanal Boyutlarının Tahmini için Yapay Sinir Ağları

Öz: Bu çalışmada, elektrokimyasal aşındırma yöntemiyle belirli bir desende oluşturulan mikro kanalların boyutunu modellemek için yapay sinir ağı kullanılmıştır. 5754 alüminyum yüzeyler maske ile kaplanmıştır. Önceden tasarlanan desen daha sonra lazerle maskelenmiş yüzeye işlenmiş, ardından elektrokimyasal aşındırma işlemine tabi tutulmuştur. Bu sayede alüminyum yüzeyde mikro desenli kanallar oluşturulur. Konsantrasyon (0.1-2.5M), elektrotlar arası mesafe (5-15cm), çalışma voltajı (15-48V) ve süre (6-30 dk) gibi elektrokimyasal aşındırma parametrelerine dayalı olarak çeşitli deneyler yapılmış ve kanalların derinliği-genişliği araştırılmıştır. Çeşitli koşullar altında yapılan çalışmalar YSA ile modellenmiş ve modelleme sonucunda elde edilen yüzey grafikleri ile girdi ve çıktı parametrelerinin sinerjik etkileri araştırılmıştır. Bu modelleme çalışması, gelecekteki ilgili çalışmalar için elektrokimyasal aşındırma ile üretilen mikro kanalın kanal boyutlarının tahminini sağlaması açısından güçlü bir araçtır. Sonuç bölümünde modellemenin yanı sıra deneylerden elde edilen bazı izlenimler ve çıkarımlara da yer verilmiştir.

Anahtar Kelimeler: Elektrokimyasal aşındırma, Mikrokanal, Modelleme, Yapay sinir ağları

1. Introduction

Micro and nanochannel manufacturing technologies show fast improvement with the increasing interest in biotechnology, microreactors, microfluidics, and nanofluids. The shape, size, and structure of the micro/nanochannel may differ according to the application types. Most microchannels have a high surface area to volume ratio. When the channel size is in the micron

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range (1-999 µm), it is called a microchannel [1]. Microfluidic devices are miniaturized fluid processing systems consisting of small channels with diameters of different micrometers, through which a small amount of fluid passes. The use of such devices has recently become popular in the medical field, in the manufacture of microreactors, fuel cell systems, heat transfer systems, and so on [2-5]. When microchannels are used as a reactor, the diffusion and mass transfer of the reagents increase due to the narrow structure of the channels. They also reduce mixing times in narrow channels. Their small dimensions prevent the formation of hot spots that often occur in batch reactors and offer higher yields for many reactions. Fast mixing and effective heat transfer offer the opportunity to run reactions with minimal waste [6,7]. In recent years, microchannel reactors have been used to drive various catalytic and photocatalytic reactions. Microchannels can be created on glass, polymeric, silicon, and metallic surfaces [8-10]. While most polymeric and glass substrates are used in biomedical and chemical devices, silicon nanostructures provide great potential in areas such as nanoelectronics [11], optoelectronics [12], and energy storage [13], energy exchange [14]. Metallic substrates are generally used for applications related to electronics and mechanical engineering [15]. Especially, since most chemical processes require high operating temperatures, these devices must be manufactured from materials that can serve at a higher temperature. For this, metals can be used because of their good mechanical properties. Therefore, metallic micro-channels and nano-channels can be successfully applied to various application areas, including valves and heat exchangers [16]. Photolithography [17], micro-cutting [18], dry etching [19], wet chemical etching [20], electro-etching [21,22], micro-electro-discharge machining [23] and laser ablation [24] can be given as an example for the production methods of microchannels. The appropriate method can be preferred according to the application areas and material types of micro-channel-based devices. Some of these methods are either expensive or time-consuming. Some also have complex operating steps. In this context, it is extremely important to find a cost-effective, simple, highly efficient manufacturing approach to enable the widespread use of microfluidic systems. One method that can be considered in this context is the electro-etching method. Electro-etching is a micromachining method that reduces the processing time without compromising the quality of the metallic sample. In addition to low cost, the advantages of electro-etching include the absence of burrs on the duct edges, processing of very fine materials, precise control of channel dimensions, and the short time between prototyping and production. However, this method also has some disadvantages. The abrasion is isotropic, that is, the channel depth is always less than the channel width [25]. However, it is possible to fix this problem with various experimental optimization studies.

Modeling studies are a powerful tool used to understand and intervene in the event under consideration. Researchers frequently use empirical modeling tools as well as analytical or semi-empirical modeling. Techniques called black-box modeling are used to understand events, particularly complex relationships. Artificial neural networks attract most of the researchers' attention in such modeling studies. Artificial neural networks are algorithms that are inspired by the learning way of the human brain and perform the learning process with the help of training data. Interest in artificial neural networks is increasing day by day in many areas such as classification, pattern recognition, signal processing, data compression, and optimization [26,29].

Artificial neural networks have been developed based on the biological nervous system. Artificial neural networks consist of neurons (process elements) that communicate interconnected. Each link has a weight value. Artificial neural cells collect the information coming from outside with a summation function and generate the output by passing it through the activation function and sending it to other cells (process elements) over the connections of the network. The optimal values of the weights must be established. Finding the most appropriate weights for the structure and input of the network takes place during the training process [30-32].

In this study, the electro-etching method was used to create patterned microchannels on an aluminum surface. Experimental studies were carried out under various operating conditions. Cell voltage, the distance between electrodes, electrolyte concentration, and time were chosen as process variables. The depth of the channels formed as a result of the experiments was measured utilizing a precision dial gauge (comparator) and the average and standard deviation of the channel depth were obtained. Matlab® image processing toolbox was also used for analyzing the channel widths. The obtained experimental results were modeled with artificial neural networks and used to estimate the operating conditions to obtain desired micro-channel depth and width.

2. Experimental Methods

In this study, microchannels were created on the metal substrate by using the electro-etching technique. NaCl (Sigma Aldrich) was used in the electrolyte solution. Electro-etching is a process that can be suitable to apply on a clean and low roughness surface. When the roughness is too high, a smooth abraded surface will not be provided even under optimum processing conditions. Polished aluminum substrates were used for this purpose. Metal substrates (properties are given in Table 1) were degreased with trichloroethylene in an ultrasonic bath, then scrubbed with soap and rinsed with distilled water. After this stage, vinyl masks were applied to the dry and clean substrates.

Table 1. Chemical composition of the 5754 aluminum

Element	Al	Fe	Cu	Si	Mn	Mg	Zn	Cr	Ti	Others
wt (%)	94.75	0.19	0.026	0.108	0.56	4.3	0.004	0.077	0.015	remainder

The pattern that was previously created using Solidworks software was marked on the masked surface with the help of a laser. Thus, the pattern was applied to the masked surface. After the masked aluminum substrates on which the pattern was transferred were prepared, an electro-etching system was installed. In this stage, NaCl (aq) was used in different concentrations (from 0.1 M to 2.5 M). 5 cm x 10 cm masked aluminum plate was used as the anode. An aluminum metal plate of the same dimensions was used for the cathode. The distance between the electrodes (5-10-15 cm) was set. A power supply was used to supply the required direct current to the system. Experiments were conducted for a certain time (6-30 min) at a fixed voltage (15-24-48 V) depending on the experimental condition. The electro-etching process is presented in Figure 1.

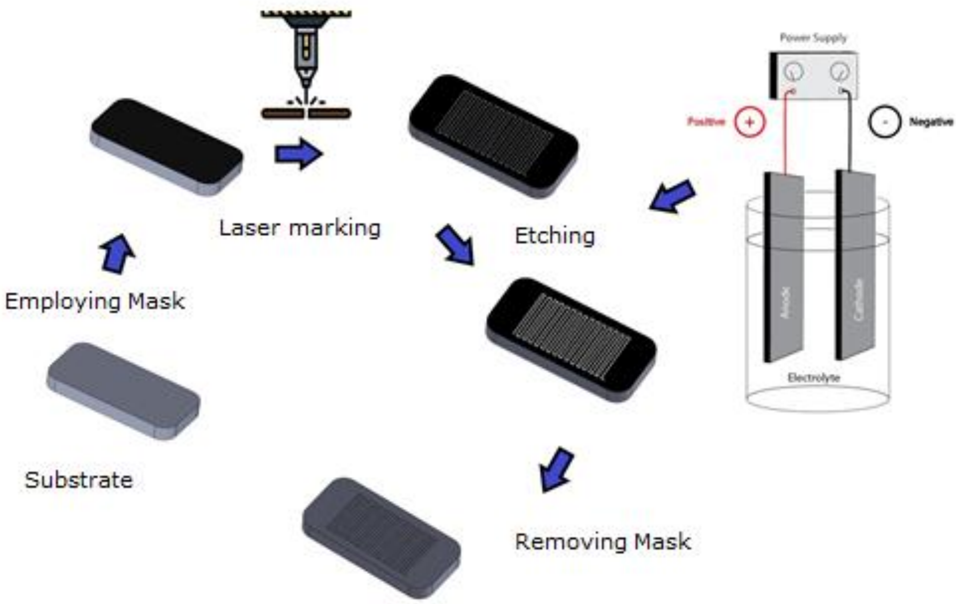

Figure 1. Microchannel preparation steps through the electro-etching process

During the etching process, the products of the reaction tend to accumulate around the anode. Stirring is required to remove the reaction products from the anode so that it does not affect the channel quality. Therefore, the electrolyte solution was mixed at 500 rpm. After the etching process was completed, the substrates with microchannel structure were taken from the system and the mask was completely removed from the surface and then rinsed with pure water. Afterward, the channel depths were measured with a precision comparator in 3 measurements (taken from the beginning, middle, and end of the channel) for each parallel channel, and the mean and standard deviations were calculated. Channel widths were obtained with Matlab using the image processing toolbox as shown in Figure 2. Then, the obtained data were modeled with artificial neural networks in Matlab environment.

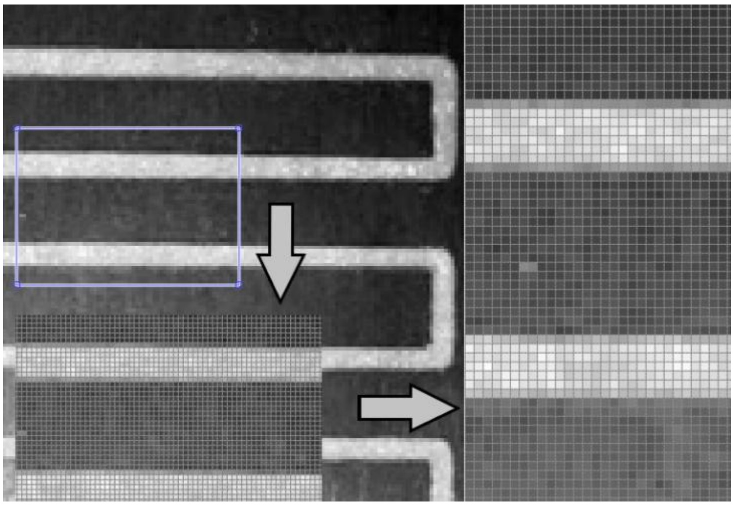

Figure 2. Channel's widths from the greyscale image by measuring the pixel size

2.1. ANN Modeling

Although there are many artificial neural network architectures, feed-forward ANN was preferred in this study. 4 inputs (distance, voltage, concentration, time) and 2 outputs (depth and width) ANN structure was designed. Results from 40 experimental runs were used for training, testing, and control of ANN. 80 % of these data were used for training, 20 % for testing, and 20 % for control. With the conducted preliminary tests, it was seen that it would be appropriate to use 10 hidden layers. In this study, 'Levenberg-Marquardt' was chosen as the optimization method to be used in the training process. Mean squared error (MSE) was selected as a performance criterion for the objective function. Also, the 'tansig' function was preferred as a transfer function.

3. Results and Discussion

Channel depths and widths were obtained as a result of experiments conducted in various conditions. With these data, the ANN modeling process was started. In Figure 3, regression graphs for training, testing, and control are shown. Since both the depth and the width are the output of the neural network, the total number of data was two-fold in the data regression graphs. The y-axis and x-axis, respectively, show the outputs predicted by the artificial neural networks and the actual values, i.e., the targets. It is seen that the regression values are very close to 1. This graph shows that the training has been carried out very well. Also, it can be said that the network performs very well against predicted data that it has never seen before.

Then, surface graphs were obtained to show the modeling and predictive power of the trained ANN with the results of experimental studies conducted with limited data. It is possible to see the synergistic effects of each parameter in the range of operating conditions. In the first of these graphs, the distance between the electrodes was kept constant at 10 cm and a 24 V power supply was provided.

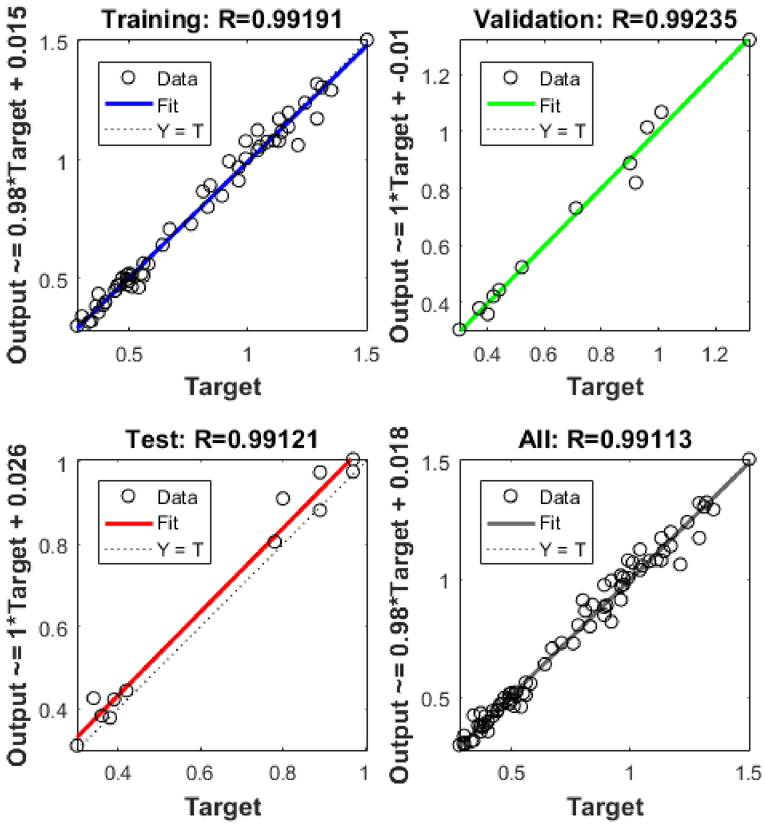

Figure 3. Regression plots of the neural networks training process

The effect of concentration and time on channel depth is shown in Figure 4. Under these conditions, while minimum channel depth was obtained at low concentration in short working times, the maximum depth was reached at 2.5 M and 30 min operating conditions. At high concentrations, faster abrasion occurs over time, while at low concentrations this effect occurs more slowly.

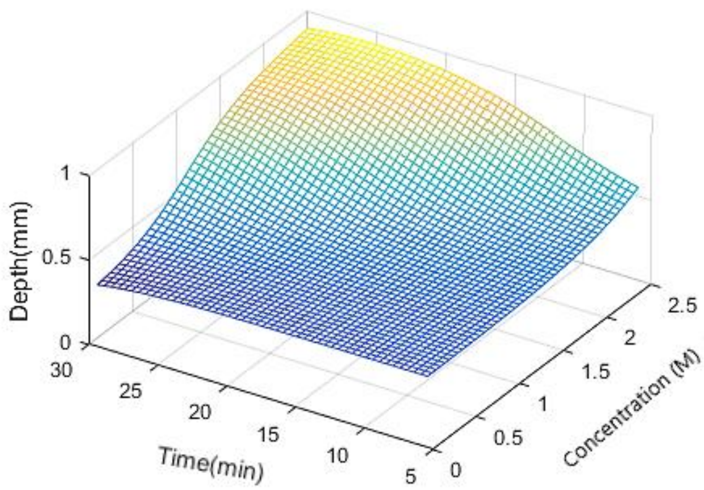

Figure 4. Effect of concentration and time on channel depth at constant voltage (24 V) and electrode distance (10 cm)

In another surface graph, it was studied at a concentration of 0.8 M and a constant voltage of 24 V. The effect of distance and time is shown in Figure 5. While the effect of the distance is much more forceful in high treatment times (30 min). This effect is relatively less in short periods. This situation occurs in the same manner for the distance.

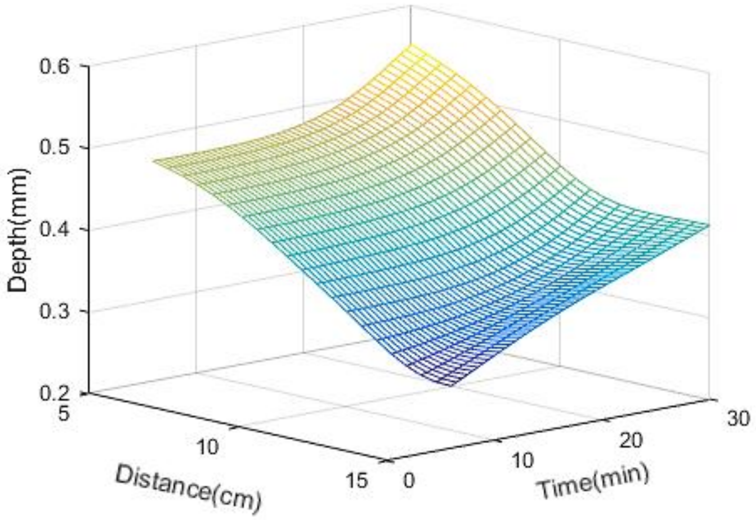

Figure 5. Effect of time and electrode distance on channel depth at the constant concentration (0.8 M) and voltage (24 V)

In the last graph electrode distance and voltage effect at the fixed concentration (0.2 M) and time (15 min) have been exhibited. As can be seen from Figure 6, the highest depth value was obtained at the high voltage and short electrode distance. As the concentration is low, of course, this effect occurred relatively little for the case under study. It can also be understood that voltage and distance have an exponentially synergistic effect. It can be seen from Figure 5 that for the high voltage at the close electrode range the highest depth was obtained. Of course, this effect occurred relatively little, as the concentration was low for the case under consideration. It can also be understood that voltage and distance show synergistic effects exponentially.

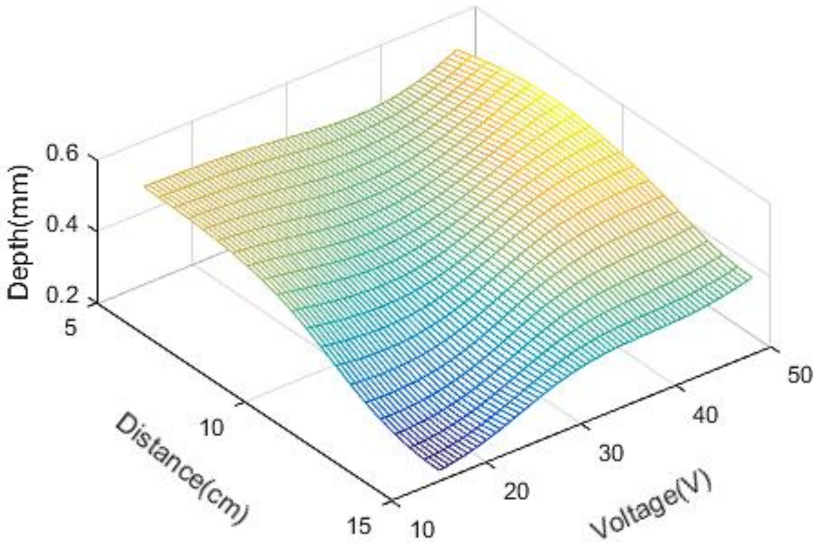

Figure 6. Effect of voltage and electrode distance on channel depth at the constant concentration (0.2M) and time (15 min)

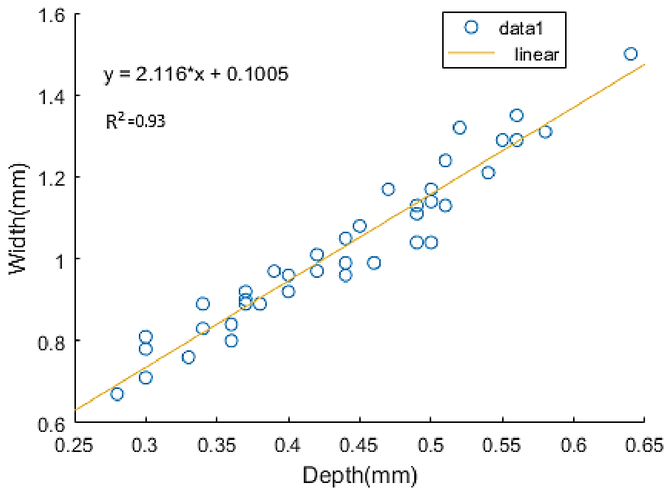

Figure 7. Correlation between the depth and width of the channel

Studies were carried out over 4 inputs and 2 outputs while modeling with ANN. Almost similar surface graphs were obtained for the channel widths. However, since the depths and widths of the channels are tightly connected, the almost linear relationship between depth and width will be shown instead of the channel width surface graphs. Figure 7 shows the correlation between channel width and depth. Channel width can be quickly predicted without the need for complex equations with this correlation. However, as can be seen from these studies conducted with a small number (40 runs) of experimental data, ANN gained a very strong prediction ability. Although the training of the network is excellent, by filling the gaps with new experiments, ANN predictive power can be further increased. Even the obtained results will be very useful in using a prediction.

Electrolyte concentration, the distance between electrodes, operating time, and applied voltage are directly dependent on the current drawn by the system. When high electrolyte concentration is used, the current drawn by the system increased. The etching environment shoved aggressive effects and caused irregularities in the channels. The etching time is inversely proportional to the current density. When low current density was used, the processing time became longer. This time can be shortened when a high current density is used. Generally, the etching process takes between a few seconds and minutes (20). In the experiments, operating at low current density, the channels became more regular, but the processing time increased considerably. Working at high voltage and low electrolyte concentrations yielded good results to shorten the extended process time and obtain smooth channels at the same time. The operation at high voltage in relatively concentrated solutions caused excessive gas emission and this also caused pitting on the surface. Another parameter that affects the channel irregularity is the distance between the electrodes. In cases where the electrodes were too close, the system again exhibited an aggressive situation. When the distance was increased, the channels became more regular again. As a result, future work can examine the channel geometry by changing the width of the gap formed by the laser engraving on the patterned surface.

4. Conclusions

Devices with microchannel architecture are used in many areas such as chemical production reactors, heat exchangers, microfluid, and nanoparticle synthesis systems. Intensive research is carried out for their development. In this study, modeling efforts were executed on microchannels manufactured by the electrochemical etching method. Studies were carried out to create micro-channels in the desired pattern on the 5754-alloy aluminum surface. Experiments were conducted under various electrochemical etching conditions; the depth and width of the channels were examined. It has been tried to reveal the relationships of the parameters by modeling the inputs and outputs of experimental runs with the artificial neural network. With a small number of data, it was seen that ANN shows good predictive performance, and the relationships of the inputs and outputs are revealed by surface graphs. Relatively high voltage (48 V), short electrode distance (5 cm), and high concentrations (2.5 M) were found to adversely affect the roughness and homogeneity of the channel. It has been also observed that channels with smoother surfaces can be obtained in milder conditions, although it causes prolongation of working times. It can be predicted under which operating conditions the desired channel depth can be reached through such studies. In addition, the width of the channel that will occur due to the isotropy at the determined depth can be estimated.

Authors' Contributions

EB and OA designed the experiment. EB conducted the experimental study. EB and OA processed and interpreted the experimental data. OA modeled the experimental data with artificial neural networks.

Both authors read and approved the final article.

Competing Interests

No conflict of interest was declared by the authors.

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