The electric field analysis of a green rust surface treatment tank for high / super alloys

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Abstract： In order to do rust surface treatment for stainless wires, this thesis proposed an electrolyzing equipment to do so. It has the following advantages: safer, cheaper and less environmental pollution. To study the performance of electrolyzing process, numerical simulation for electric fields will be conducted by using COMSOL Multiphysics software. Taguchi methods was also involved to obtain better design of the electrodes arrangement. This thesis used COMSOL Multiphysics software to simulate the current density of these electrodes. And we found that biggest current density was presented by the semi-circular electrode, followed by the concave electrode and the last was the plate electrode. And then we combined COMSOL Multiphysics software with Taguchi methods to simulate optimal parameters of the strongest electric field. The results revealed that closer distance between the metal strip and the electrodes increased the current density.

Keywords: Stainless wires, Electric field, COMSOL Multiphysics, Taguchi methods

1. Introduction

Acid chemicals like hydrochloric acid, sulfuric acid and nitric acid are usually mixed for acid pickling in traditional rust removal process; however, they may generate waste water and exhaust that can result in tremendous pollution and damage to human bodies and the environment. From the aspect of manufacturing and processing, improper operation may cause excessive acid pickling and worn metals. Thus, a great amount of water is required anytime for rinsing, which may increase processing costs. Serious consequences may be resulted from power failures and suspension of water supply and work. Based on the observations of the phenomena above, a special electrolyte will be researched and developed for the electrolytic pickling process to reduce pollution and unnecessary processing waste. Less damage will be made to the environment after comparing this process and the previous acid pickling process.

The specially developed electrolyte that causes less environmental pollution will be adopted for exploration of its performance in electrolytic pickling in this dissertation and analysis of the electric field of the electrolyzer will be the main direction for study.

2. Direction of research and description of issues

2.1 Direction of research

Analysis of the optimal configuration of the electrodes in the electrolyzer is the main issue in this research. It is expected the maximum current density and the optimal electrolysis effect can be achieved and electricity can be saved by optimizing the electrode configuration and parameters. Two directions will be focused in this research. First, COMSOL Multiphysics, an existing simulation software, will be used for decision of a more superior electrode configuration. Then, Taguchi methods will be applied to the more superior electrode configuration for optimization of detailed scales of the electrodes.

2.2 Description of influence of electric fields on the electrolyzer

Two pieces of electrodes as the cathode and the workpiece as the anode are placed together into the electrolyzer that is filled with electrolyte. The conditions of (1) the locations where the electrodes and the workpiece are placed, (2) the distance between the electrodes and the workpiece, (3) dimensions of the electrodes, and (4) the volume of the electrolyte will influence the current density or voltage during the electrolysis process and further affect the quality of electrolysis or increase the cost of electric potential. Consequently, the optimum parameters need to be found out through experimental design of Taguchi methods.

2.3 COMSOL Multiphysics, numerical simulation software

The manipulation of COMSOL Multiphysics can be divided into six steps, including (1) application modes, (2) CAD draw mode, (3) physics mode, (4) mesh mode, (5) solve mode, and (6) postprocessing mode.

3. Theoretic Analysis

3.1 Laws related to electrolysis

3.1.1 Electrolysis

The process of current flowing from anode to cathode through electrolyte or electrolyte solution and causing reduction-oxidation is called electrolysis. When ionic compounds are in a solution, they all become electrolytes. As ions can move freely, they can conduct electricity.

3.1.2 Maxwell's equations

Suppose electric potential and charge source are zero in a free space, then Maxwell's equation is as follows:

$$\nabla \bullet E_f = 0 \quad (1)$$

$$\nabla \bullet B = 0 \quad (2)$$

$$\nabla \times E_f = -\frac{\partial B}{\partial t} \quad (3)$$

$$\nabla \times B = \mu_0 \varepsilon_0 \frac{\partial E}{\partial t} \quad (4)$$

where E_f is the electric field and the SI unit is tesla;

B is the magnetic field and the SI unit is tesla;

$\frac{\partial}{\partial t}$ is the partial derivative with respect to time and the SI unit is per second;

ε_0 is the electric constant and the SI unit is farads per meter;

μ_0 is the magnetic constant and the SI unit is newtons per ampere squared

Careful observations of Maxwell's equations indicate a specific explanation that how electromagnetic waves transmit in a space. As a result, changes to the magnetic field not only influence the electric field, but also affect distributions of the current density.

3.1.3 Faraday's law

According to Faraday's law, the current density will influence electrolytic formations.

3.1.4 Ohm's law

According to Ohm's law, the electrolyte can be served as an electric resistance during electrolysis. When the potential is fixed, the resistance becomes less and the current becomes greater and vice versa.

3.1.5 Electric conductivity

When the electric conductivity equals the constant, the current density becomes greater and the electric field is stronger.

3.1.6 Current density

Current density refers to the density of flowing charges; that is, current/per section area and the SI unit is ampere/meter^2 (A/m^2).

3.2 Electrolyte, current density and current efficiency [5]

Functions of the electrolyte are:
(1) to carry current to the place between the electrode and the workpiece,
(2) to solve the anode of the workpiece and generate processed products, and
(3) to remove heat, products and bubbles resulted from processing.

As the electrolyte is conductive, different current densities and current efficiencies will be formed on the surface of the workpiece affecting electrolytic quality. Various current densities may cause different current efficiencies at a spot.

3.3 Electromagnetics of COMSOL Multiphysics [1]

Electromagnetics may couple various partial differential equations for Maxwell's equations and construct the electromagnetic field by the engineering model for simulation and visualization. Data or correlations of geometry, fields, wavelengths, material properties and initial conditions may also be used for establishment of meshes and the solution can be obtained by iteration.

3.4 Process of Taguchi methods [2]

Data analysis of Taguchi methods can be

divided into the following five steps:

1. to decide quality characteristics and calculate data of each experiment or simulate signal-to-noise ratios of the data,
2. to formulate the Response Table and the Response Graph,
3. to conduct Analysis Of Variance (ANOVA),
4. to presume the optimization theory, confidence intervals and the best combination of factors, and
5. to confirm the experiments

4. Results and Discussion

4.1 Electric field analysis of the electrolyzer

COMSOL Multiphysics was used for mapping in this research to build the geometric model of the electrodes and the workpiece configured in the electrolyzer. Then, meshes were established and subdomain settings and boundary settings were made for calculation. Upon completion of computation, the postprocessing mode was applied for analysis and data were revealed.

As shown in Fig. 1, boundary settings are: 1. black boundary (edge of electrolyzer) is insulated, 2. electrodes are grounded, and 3. constant voltage (0.013v) is set for the metal strip.

Current densities of nine spots around the workpiece were measured in order for comparison as shown in Fig. 2.

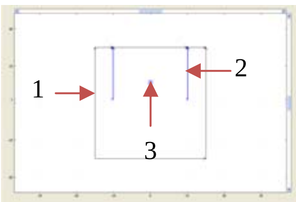


Fig. 1 Boundary Settings for Electric Field Analysis

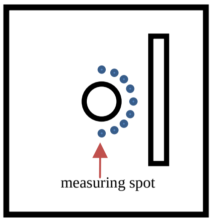


Fig. 2 Measurements of Nine Spots around Workpiece for Comarison

4.2 Comparison of electrodes of different shapes by electric field analysis

Current densities of the electrodes with different shapes were compared by the same settings of the same specifications for further analysis. The fluctuating curve was due to distribution of electric lines around the metal strip during electrolysis as shown in

Fig. 3. Comparisons showed that the rhombus electrode was neglected since processing was not easy and concave, circular and semi-circular electrodes were similar. Therefore, semi-circular electrodes were adopted for in-depth exploration. The plate electrode was chosen for analysis. Finally, an optimization experiment was made to the electrodes of the electrolyzer designed by China Steel Machinery Corporation for comparison.

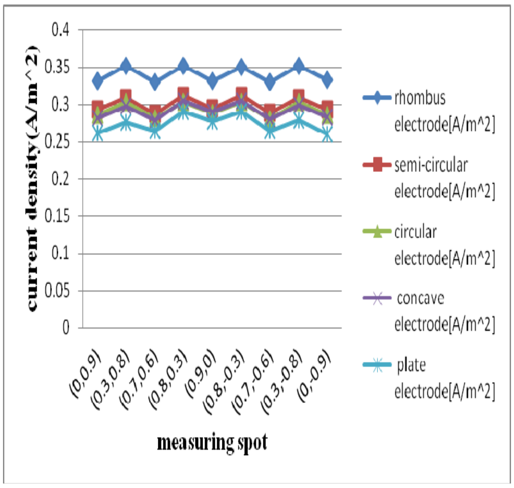


Fig. 3 Comparison of Results Rendered by Electrodes of Different Shapes

4.3 Analysis of Taguchi methods

Settings of the semi-circular, plate electrodes and the electrodes in a tank designed by China

Steel Machinery Corporation were configured for the experiment. Design of the experiment would be based on Taguchi methods to explore the influence of each factor on current density. The L_9 orthogonal arrays were adopted and the quality goal of current density was analyzed by 'larger the better.' All results indicate the distance between electrodes and the metal strip was the most influential parameter and improved data were within the confidence intervals. Consequently, these results can be used for reference and described as follows:

4.3.1 Semi-circular electrode

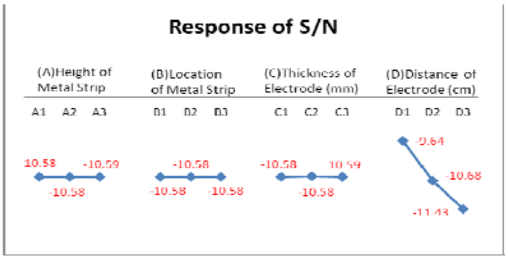


Fig. 4 Response Graph of Factors Configured in Tank with Semi-circular Electrodes

Table 1 Optimum Combination of Factors

	LEVL 1	LEVL 2	LEVL 3
(A)Height of Metal Strip	Top	Middle	Down
(B)Location of Metal Strip	Left	Middle	Right
(C)Thickness of Electrode (mm)	1	2	3
(D)Distance of Electrode (cm)	3	4	5

Table 2 Improved Factors Configured in Tank with Semi-circular Electrodes

	S/N	
	Simulated	Predicted
Original Data	−10. 68146	−10. 67568
Optimized	−9. 630161	−9. 629079
Improved	1. 0512971	1. 0466

Table 3 Confidence Intervals of Improved Semi-circular Electrodes

Confidence Interval	Positive	−9. 627626
	Negative	−9. 630532

4.3.2 Plate electrode

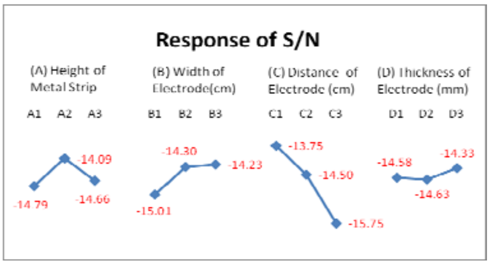


Fig. 5 Response Graph of Factors Configured in Tank with Plate Electrodes

Table 4 Optimum Combination of Factors

	LEVL 1	LEVL 2	LEVL 3
(A) Height of Metal Strip	Top	Middle	Down
(B) Width of Electrode(cm)	12	20	28
(C) Distance of Electrode (cm)	6	10	14
(D) Thickness of Electrode (mm)	1	2	3

Table 5 Improved Results of Factors Configured in Tank with Plate Electrodes

	S/N	
	Simulated	Predicted
Original Data	−14. 12299	−13. 97134
Optimized	−12. 87542	−12. 85604
Improved	1. 2475729	1. 1153

Table 6 Confidence Intervals of Improved Plate Electrodes

Confidence Interval	Positive	−12. 82458
	Negative	−12. 8875

4.3.3 Electrodes in tank designed by China Steel Machinery Corporation

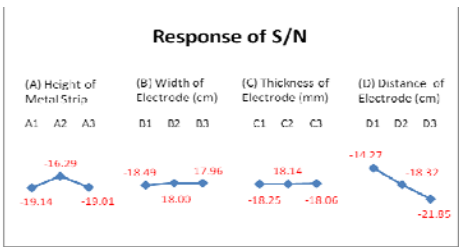


Fig. 6 Response Graph of Factors Configured in Tank with Electrodes Designed by China Steel Machinery Corporation

Table 7 Optimum Combination of Factors

	LEVL 1	LEVL 2	LEVL 3
(A) Height of Metal Strip	Top	Middle	Down
(B) Width of Electrode (cm)	2	3	4
(C) Thickness of Electrode (mm)	1	2	3
(D) Distance of Electrode (cm)	3	6	10

Table 8 Improved Results of Factors Configured in Tank with Electrodes Designed by

China Steel Machinery Corporation

	S/N	
	Simulated	Predicted
Original Data	-16.30608	-16.3054
Optimized	-12.13434	-12.125796
Improved	4.1717364	4.1796

Table 9 Confidence Intervals of Improved Electrodes Designed by China Steel Machinery Corporation

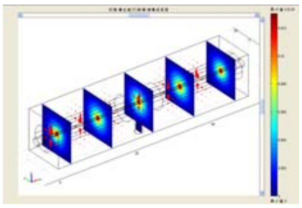
Confidence Interval	Positive	-12.07609
	Negative	-12.1755

4.3.4 Voltage determined by constant current after Taguchi methods

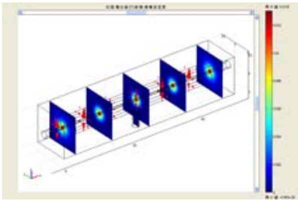
Constant voltage was provided after improving Taguchi methods. When electrodes got closer to the metal strip, the current density became greater. Voltage became less when electrodes got closer to the metal strip after giving constant current.

4.4 3D electric field simulation

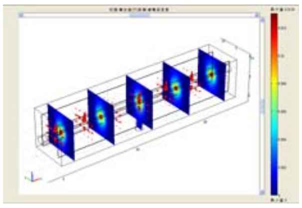
Upon completion of improving Taguchi methods, 3D electric field simulation was conducted to observe if the electric field helped even distribution of the current density in the whole tank. The results corresponded as shown in Fig. 7.



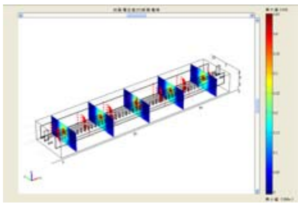
(a) Semi-circular Electrode



(b) Circular Electrode



(c) Plate Electrode



(d) Tank with Electrodes Designed by China Steel Machinery Corporation

Fig. 7 3D Electric Field Simulation

4.5 Computation of current to be provided during electrolysis

✧ where 40A/dm^2:

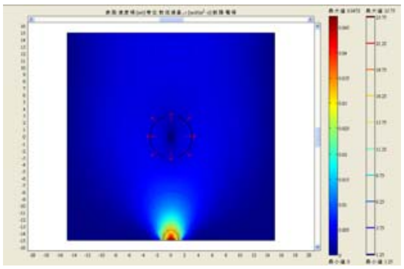
6.5cm×3.14×500mm×40 A/dm^2/10000=40.82A

✧ where 20 A/dm^2:

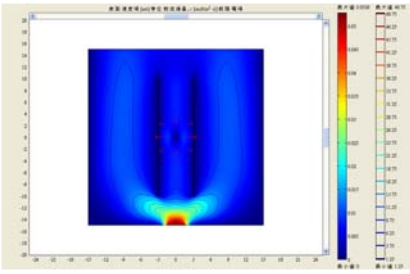
6.5cm×3.14×500mm×20 A/dm^2/10000=20.41A

4.6 Comsol Multiphysics

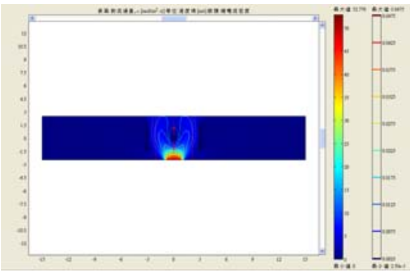
Coupled simulation of the electric field, flow and mass transfer was made as shown in Fig. 8.



(a) Coupled Simulation of Electric Field, Flow and Mass Transfer for Semi-circular Electrode (3cm)



(b) Coupled Simulation of Electric Field, Flow and Mass Transfer for Plate Electrode (3cm)



(c) Coupled Simulation of Electric Field, Flow and Mass Transfer for Electrode (3cm) Designed by China Steel Machinery Corporation

Fig. 8 Coupled Simulation Graph of Electric Field, Flow and Mass Transfer

5. Conclusion

Conclusions were reached after analysis and summarized as follows:

1. After comparing the electrodes of different shapes by electric field simulation, the current density rendered under the same specifications from the highest to the lowest in order is: (1) rhombus electrode, (2) semi-circular electrode, (3) circular electrode, (4) concave electrode and (5) plate electrode.
2. After improving Taguchi methods, it is found the distance between the electrode and the metal strip is the most influential parameter.
3. Upon improving experimental design of Taguchi methods, constant voltage was provided and the current density became greater when the electrode got closer to the metal strip. Voltage became less when the electrode got closer to the metal strip after giving constant current.
4. Observations of the 3D electric field simulation show that the electrolyzer may generate an even electric field enhancing electrolytic pickling.

6. References

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