An Experimental Study on the Technique Optimization in Localization Process of 4J36 Invar Alloy-A Micro-Electrochemical Machining Perspective

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Abstract. This study introduces electrochemical processing into the processing of 4J36 Invar alloy to obtain higher processing accuracy. An experimental study based on central composite design (CCD) was carried out to analyze the effects of voltage, duty cycle, feed rate, and inter-electrode gap on the localization of Invar processing. The response surface method is used to establish a mathematical model between process parameters and processing locality. The model shows that the minimum Side Gap is 158.7 μm, and the prediction results are verified by experiments. The prediction error of the mathematical model is 1.44%, which means that the proposed optimal mathematical model can solve the optimal processing parameters of 4J36 Invar alloy. It has a positive significance for the wide application of Invar.

1. Introduction

Electrochemical processing, also known as Electrochemical Machining (ECM), is a process in which an anodic dissolution of a metal workpiece occurs in an electrolyte[1,2]. The whole process is completed by the synergistic action of electrochemical, flow field and electric field. It has the advantages of high productivity, no tool loss, no cutting stress, and the principle of ion erosion makes it have the potential of fine and precise processing. Electrochemical machining is suitable for the processing of difficult-to-machine materials and complex shapes. It has been widely used in the manufacturing industries of aviation, aerospace and molds[3]. Invar is an alloy containing 64% iron and 36% nickel. Its coefficient of expansion is very low, with a value of 1.8×10⁻⁶ cm/℃ and a temperature ranging from a low temperature of -196℃ to a temperature of 260℃. This value is twice as low as stainless steel and 100 times lower than iron, which makes Invar alloy widely used in various fields[4,5]. The process parameters in electrochemical machining have an important influence on the processing precision of Invar. S.H.Kim et al.[6] The surface quality of Invar were investigated under different voltage and electrode shapes. Choi S-G et al.[7] The current density in electrochemical machining was studied by finite element analysis. K.H.Chun et al.[8] The processing properties of different electrolyte compositions for electrochemical processing of Invar alloys were investigated. The electrolyte components under the optimum process conditions were determined. However, the influence of different process parameters on the accuracy of electrochemical processing of Invar alloy has paid little attention.

In this paper, the influence of electrochemical processing parameters on the localization of 4J36 Invar alloy is studied. The experimental study based on the central composite design (CCD) is carried out to analyze the effects of voltage, duty cycle, feed speed and gap between electrodes on the localization of 4J36 Invar alloy processing. In the experiment, the localization is represented by the processing Side
Gap, and the mathematical model between the processing parameters and the localization is established by the response surface method\cite{9}. To solve the problem of optimum processing conditions.

2. Experiment

2.1. Experimental Set-Up

The structure of the ECM experimental system is shown in Fig. 1 and 2. The experimental system consists of four subsystems: the power supply system, the machine tool system, the microelectrode system, and the processing control and monitoring system. The power supply system can provide variable pulse voltage, duty cycle, pulse frequency. The machine tool system ensures high precision in micro electrochemical machining. The microelectrode system consists of a tool electrode, an electrolytic cell, an Invar alloy. The 4J36 Invar workpiece is fixed on the electrolyzer and placed on the lifting platform. The machining control and monitoring system has a motion control card and Supereyes. supereyes monitors the machining process and captures images. The material used in the experiment was 4J36 Invar. table 1 lists the chemical composition of 4J36 Invar.

Table 1. Chemical compositions of magnesium 4J36 invar alloy.

| Components | Fe  | Ni  | Cr  | C   | Mn  | Si  | Co  | P   | S   |
|------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Percents   | 62.64 | 36  | 0.2 | 0.03 | 0.4 | 0.2 | 0.5 | 0.02 | 0.01 |

2.2. Experimental Arrangement

Voltage (6, 8, 10V), duty cycle (40, 60, 80%), feed rate (0.5, 1.5, 2.5μm/s) and inter-electrode gap (100, 150, 200μm) are used in electrochemical machining. As the main processing technology parameters, the test is designed based on the central composite design, considering three factors and three levels. Therefore, 30 sets of tests (including 6 sets of repeated tests) were carried out, and the microelectrode system is shown in Table 2. The specific experimental steps are:

a) The anode workpiece is placed in an ultrasonic cleaner for ultrasonic cleaning to remove surface impurities to prevent interference with the experiment.

b) Place the workpiece on the electrolyzer fixture and install the tool cathode to adjust the inter-electrode gap.

c) Pour the configured 1mol/L NaNO3 + 0.1mol/L C6H8O7 electrolyte into the electrolytic cell to soak the workpiece for 5-10 minutes. The workpiece and the electrolytic cell are cleaned after processing.

d) The Side Gap of the machined hole was observed using a scanning electron microscope and the results were recorded (Side Gap equals hole radius minus cathode radius).
2.3. Result and Discussion
The design of the test and the test results obtained are shown in Table 3. The experimental results show the influence of process parameters on the Side Gap, as shown in Fig 3. It can be seen that the Side Gap increases as the pulse voltage and duty cycle increase. It decreases as the feed rate increases. The inter-electrode gap has less influence on the Side Gap. The value of the Side Gap varies within a small range.

Table 2. Experiment parameters.

| parameter        | values                                      |
|------------------|---------------------------------------------|
| Size of cathode  | ![cathode image]                             |
| Size of anode    | 25mm×25mm×0.3mm                             |
| Cathode material | H62 brass                                   |
| Anode material   | 4J36 invar alloy                            |
| Electrolyte      | 1mol/L NaNO₃+0.1mol/L C₆H₈O₇                |
| Spindle speed    | 4000 rpm                                    |

3. Optimization

3.1. Development RSM models
The response surface method is used to establish a mathematical model of the actual factors between the process parameters and the machining Side Gap. The model includes linear correlations and interactions. As shown below:

\[
\text{Side\,Gap} = 182.63 + 9.56 \times A + 4.22 \times B - 11.44 \times C + 1.5 \times D + 3.44 \times AB + 2.31 \times AD - 2.94 \times BC
\]

(1)

Among them, A, B, C, and D are voltage, duty ratio, feed speed, and inter-electrode gap, respectively. In order to determine the reliability of the model and compare the influence of process parameters on the Side Gap, a second-order model analysis of variance was performed. Table 4 shows the ANOVA results for the Side Gap. Among them, the R² term is 0.9213, which proves the reliability of the model.

3.2. Parametric influence
As shown in Fig 4, the effect of process parameters synergistically on the Side Gap can be seen.

3.3. Verification
According to the mathematical model, the processing parameters and predicted values of the minimum Side Gap can be obtained, and the results of experimental verification are shown in Table 5. It can be seen that the error is 1.44%. The fig 5. shows the processing results of the optimized parameters.
Table 3. Experiment result.

| No | Voltage | Duty Cycle | Feed Speed | Interpolar Gap | Side Gap |
|----|---------|------------|------------|----------------|---------|
| 1  | 10      | 80         | 2.5        | 200            | 194     |
| 2  | 8       | 40         | 1.5        | 150            | 178     |
| 3  | 8       | 60         | 0.5        | 150            | 193     |
| 4  | 8       | 60         | 1.5        | 150            | 183     |
| 5  | 10      | 80         | 0.5        | 100            | 209     |
| 6  | 6       | 40         | 0.5        | 200            | 182     |
| 7  | 10      | 40         | 2.5        | 200            | 175     |
| 8  | 8       | 60         | 1.5        | 150            | 180     |
| 9  | 6       | 40         | 0.5        | 100            | 181     |
| 10 | 8       | 60         | 1.5        | 100            | 175     |
| 11 | 10      | 60         | 1.5        | 150            | 192     |
| 12 | 10      | 80         | 2.5        | 100            | 181     |
| 13 | 8       | 60         | 1.5        | 150            | 186     |
| 14 | 6       | 80         | 0.5        | 200            | 189     |
| 15 | 8       | 60         | 2.5        | 150            | 174     |
| 16 | 10      | 80         | 0.5        | 200            | 218     |
| 17 | 8       | 60         | 1.5        | 150            | 185     |
| 18 | 8       | 60         | 1.5        | 200            | 175     |
| 19 | 6       | 80         | 2.5        | 200            | 152     |
| 20 | 8       | 60         | 1.5        | 150            | 179     |
| 21 | 6       | 80         | 2.5        | 100            | 164     |
| 22 | 6       | 40         | 2.5        | 100            | 160     |
| 23 | 10      | 40         | 0.5        | 200            | 201     |
| 24 | 8       | 80         | 1.5        | 150            | 189     |
| 25 | 6       | 40         | 2.5        | 200            | 169     |
| 26 | 10      | 40         | 2.5        | 100            | 178     |
| 27 | 8       | 60         | 1.5        | 150            | 182     |
| 28 | 6       | 60         | 1.5        | 150            | 175     |
| 29 | 10      | 40         | 0.5        | 100            | 188     |
| 30 | 6       | 80         | 0.5        | 100            | 192     |
Figure 3. Effect of process parameters on Side Gap.

Table 4. ANOVA results of Side Gap.

| Source   | Sum of Squares | df | Mean Square | F-value | p-value |
|----------|----------------|----|-------------|---------|---------|
| Model    | 4775.19        | 7  | 682.17      | 36.80   | < 0.0001 | significant |
| A        | 1643.56        | 1  | 1643.56     | 88.67   | < 0.0001 |
| B        | 320.89         | 1  | 320.89      | 17.31   | 0.0004   |
| C        | 2357.56        | 1  | 2357.56     | 127.19  | < 0.0001 |
| D        | 40.50          | 1  | 40.50       | 2.19    | 0.1535   |
| AB       | 189.06         | 1  | 189.06      | 10.20   | 0.0042   |
| AD       | 85.56          | 1  | 85.56       | 4.62    | 0.0429   |
| BC       | 138.06         | 1  | 138.06      | 7.45    | 0.0122   |
| Residual | 407.78         | 22 | 18.54       |         |         |
| Lack of Fit | 370.28    | 17 | 21.78       | 2.90    | 0.1212   | not significant |
| Pure Error | 37.50       | 5  | 7.50        |         |         |
| Cor Total | 5182.97      | 29 | R^2 = 0.9213|         |         |

Table 5. Results of confirmatory experiment.

| Exp No | Parameters settings | Side Gap |
|--------|----------------------|----------|
| A      | B        | C      | D | Exp | Pred | Error% |
| 1      | 6        | 80     | 2.5 | 200 | 161  | 158.7  | 1.44% |
4. Conclusions

- The factor that has the greatest influence on the Side Gap of the hole is the feed speed, followed by the pulse voltage. The inter-electrode gap has less effect on the Side Gap.
- A response diagram of the synergistic effect of the process parameters on the Side Gap of the hole is obtained.
- Establish a mathematical model of process parameters and pore Side Gap in the process of micro-electrochemical machining of 4J36 Invar alloy. The optimum process parameters were determined and verified by experiments with an error value below 5%.

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