

Optimization Design of the Structure for Miniature Engraving Machine based on Orthogonal Experiment and Grey Correlation Analysis

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Abstract

This paper presents an optimization design method of structure for miniature engraving machine to improve the comprehensive performance of static and dynamic. Firstly, the finite element model of miniature engraving machine is established in the ANSYS software. Secondly, based on this finite element model, static and dynamic analysis is implemented. Thirdly, multi-objectives optimization based on orthogonal experiments is processed by taking the mass of the structure, the maximum deformation, the maximum stress and the first-order natural frequency as the objective functions and choosing three major sizes which have the most remarkable influences on the above mentioned objectives as the design variables. Finally, the optimal solution of optimization design is searched by adopting the grey relational analysis which makes the mass reducing 3.422%, the maximum deformation reducing 14.658%, the maximum stress reducing 10.621% and the first-order natural frequency increasing 7.014% simultaneously. Research indicates that orthogonal experiment method and the grey correlation analysis method has higher practicability.

Keywords: Optimization design; Multi-objectives; Orthogonal experiment method; Grey correlation analysis

Introduction

Miniature engraving machine as a kind of NC machine tools, such as milling machine, mainly used in advertising, printing, decoration of jewelry and other industries [1]. In order to ensure the structural stability and machining precision of engraving machine when the machine is processing products with high speed and high acceleration in the feed movement, it is necessary to require the engraving machine to have good static and dynamic performance.

To improve the structural performance of engraving machine, various optimization design methods and strategies have been investigated by many researchers [2,3]. Li Shihong [4] did static and dynamic analysis and optimization design on the structure of a miniature engraving machine using ANSYS software. Through the optimal design of the X-axis and Y-axis guides, the natural frequency of the overall structure has been improved and the maximum deformation has been decreased. Yan Jianyong [5] obtained good results by analyzing and optimizing the structure of beam of CNC engraving machine with the help of ANSYS software. Luan Lujie [6] processed the optimal design of engraving machine and improved the intensity and rigidity of the beam by changing the wall thickness and material. Sun Peng [7] adopted single factor method to improve the static and dynamic performance of engraving machine, and verified through experiments. However, all above research have too much subjective consciousness, and the finally optimized solution generally was not optimal. With the development of computer technology, a lot of artificial intelligence methods such as Orthogonal Experiment Method [8], Grey Correlation Analysis Method [9-12], Genetic Algorithm [13-16] and so on are used in the structural optimization. But, in the field of optimization of engraving machine, there is no one has applicate these intelligent methods for structural optimization. So In this paper, a new method for structural optimization of miniature engraving machine based on orthogonal experiment and grey correlation analysis is presented. By adopting the method to optimize the miniature engraving machine, the result of optimization indicates that: the mass has reduced 3.422%, the maximum deformation has reduced 14.658%, the maximum stress has reduced 10.621% and the first-order natural frequency has increased

7.014%, simultaneously. The comprehensive performance of static and dynamic have been highly improved.

This paper is organized as follows: In Section 2, the overall structure is described briefly. In Section 3, static and dynamic analysis of miniature engraving machine are processed. In Section 4, the orthogonal experiment is implemented. In Section 5, the multi-objective comprehensive evaluation model based on grey relational analysis is established and the optimal solution is searched. In Section 6, the results are analyzed and discussed. Section 7 summarized the proposed method for optimal design and the conclusions as well as future work.

Description of Overall Structure

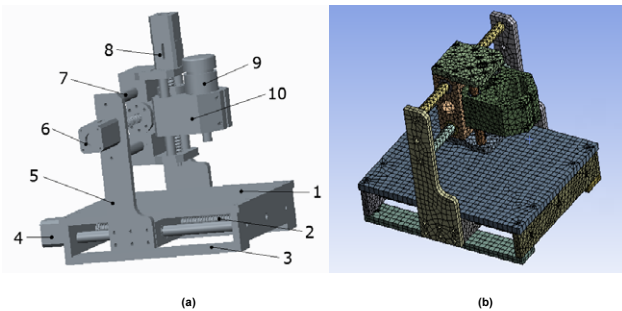
The overall structure of the miniature engraving machine, as shown in Figure 1a, consists of the base, workbench, cylindrical guides, uprights, ball screws, sliders, stepper motors, motor spindle, spindle component, etc. The engraving machine adopts gantry mobile structure. When it is in processing, the spindle components on which a high-performance motor spindle is installed moves along the beam (X-axis guide), thus realizing the engraving width. Likewise, the beam connected with the Y-axis guide through the uprights can achieve engraving length and the spindle component can realize engraving depth by moving up and down along the Z-axis guide. Besides, there are three independent stepper motors, driving 3 pairs of ball screws which control the motion of X, Y, Z axis to make sure that the cutter location accurately in the transmission mechanism of this prototype.

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1- workbench, 2-ball screw, 3-the base, 4-stepper motor of Y axis, 5-upright, 6- stepper motor of X axis, 7-cylindrical guide, 8- stepper motor of Z axis, 9-motor spindle, 10-spindle component

Figure 1: Miniature engraving machine. (a) Overall structure, (b) Finite element model.

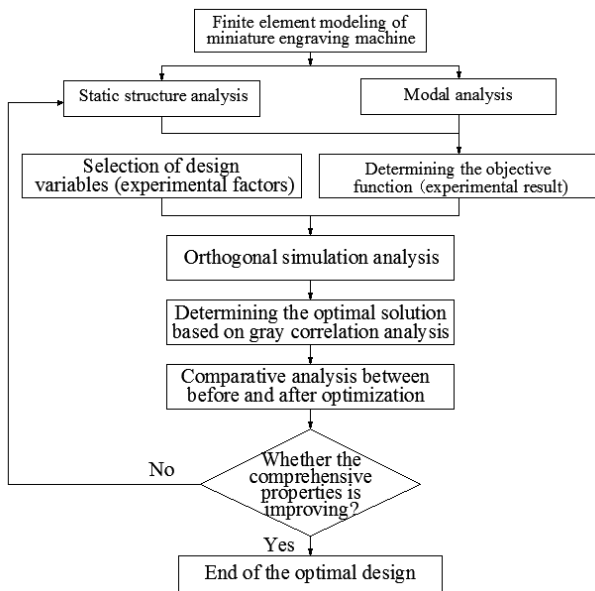


Figure 2: The technical route of engraving machine optimization.

Finite Element Analysis of Engraving Machine

Firstly, a three-dimensional geometric model of miniature engraving machine is established in the PRO/E software, and then imported to ANSYS software for pre-process of finite element analysis. Taking into account its complex structure, the unit division method combining intelligent divided network and human intervention is used in the meshing and the motor spindle and stepper motors are removed in that their complex materials are considerably inconvenient for analysis. The numbers of nodes and units are 85137 and 40318. The base is applied fixed restraint and the material of all miniature engraving machine is set to aluminum alloy [17]. Finally, the meshed finite element model of miniature engraving machine is shown in Figure 1b. After the completion of above settings, actual working conditions can be simulated. On this basis, CAE analysis on engraving machine according to the technical route shown in Figure 2 can be expanded.

Static structural analysis

For the miniature engraving machine working in the actual

condition, heat source of electricity produced by the rotation of the spindle has little effect on deformation of the overall structure, therefore, this paper will mainly analyze the static structural deformation caused by mechanical force resulted from the motion of cutter.

The static structural analysis of engraving machine is proceeding in the structural analysis of the finite element statics module of ANSYS software. First, displacement constraints are imposed on engraving machine. Actually, the force condition of engraving machine is mainly derived from the cutting force transferred from the motor spindle and gravity of the motor spindle. To simplify it, we apply 100N respectively to the spindle component on X, Y, Z directions which is approximately equivalent to that complicated force condition. After static structural analysis simulation, the mechanical deformation is shown in Figure 3, from which shows that the maximum mechanical deformation of the engraving machine is about 0.156 mm, meaning the deformation is small; the mechanical stress shown in Figure 4 illustrates that the maximum mechanical stress is 12.889 MPa which is within the range of the allowable stress of material and meets the strength designing requirement. Although the results indicate engraving machine damage

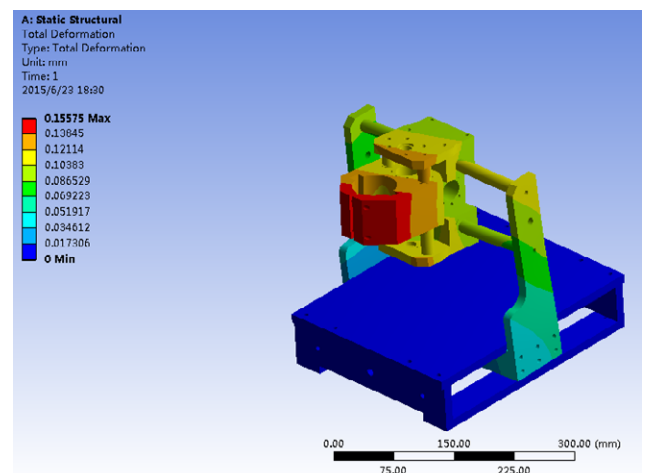


Figure 3: Distribution of deformation of the original miniature engraving machine.

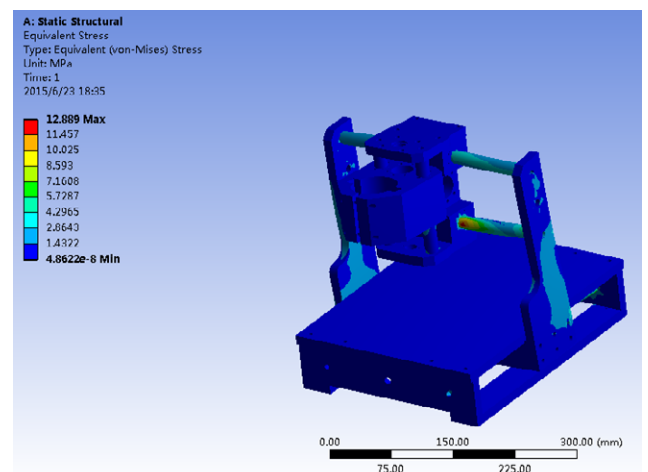


Figure 4: Stress distribution of the original miniature engraving machine.

and excessive deformation will not occur in high-speed processing conditions, it is in desperate need to minimize the mechanical deformation and stress by doing structural optimization, furthermore, to improve the processing accuracy and stability.

Modal analysis

Since vibration exists inevitably when engraving machine is in processing, and the processing accuracy of machine will be affected by the vibration produced by so many parts such as spindle component, uprights, base and so on. In return, these vibrations also affect the accuracy and stability of engraving machine. In summary, it is indispensable to do modal analysis on the structure of engraving machine.

The purpose of modal analysis focusing on natural frequency and mode shape is to identify the vibration characteristics of engraving machine [18]. Moreover, the vibration characteristics of the structure are almost determined by those of the low-order modes in the finite element modal analysis of structure. Therefore, only the first four natural frequencies and mode shapes of engraving machine structure will be studied here by using subspace iteration method in the modal analysis of ANSYS software under two hypotheses including no damping and free vibration. Based on that, the results are shown in Table 1 with the finite element solution of natural frequencies and mode shapes, from which it can be concluded that the swing direction of the first-order modal shape of engraving machine is consistent with the axial of motor spindle. Besides, the work frequency of the motor spindle is about 156. So the value is very close to the first-order modal of engraving machine. Therefore, it is necessary to do optimization analysis to improve the vibration resistance and reduce the influence of the amplitude of the vibration modes of axial deformation of the motor spindle.

Orthogonal Optimization Design of Engraving Machine

Determination of the optimal goals and the design variables

According to analysis mentioned above, the maximum mechanical deformation, maximum stress and the first-order natural frequency are goals of optimization. More specifically, is to minimize the maximum mechanical deformation, maximum stress and improve the first-order natural frequency. But in this way it tends to increase the mass of engraving machine that doesn't meet the requirement of light-weight design in modern CNC machine. Therefore, the mass of engraving machine is taken as another optimal goal. Considering its complex structure and numerous design sizes, different sizes will have influence on static, dynamic and other properties on varying degree. So this paper choose three major sizes including the length of the Y-axis guides (L), the thickness of the spindle components (T) and the height of the uprights (H) as the design variables because they have the most remarkable influences on the above mentioned goals such as the maximum deformation occurred on the spindle component, the maximum stress occurred in the Y-axis guides and the maximum deformation occurred on the uprights in modal analysis. The figures of three sizes are shown in Figure 5, and the initial length of the Y-axis

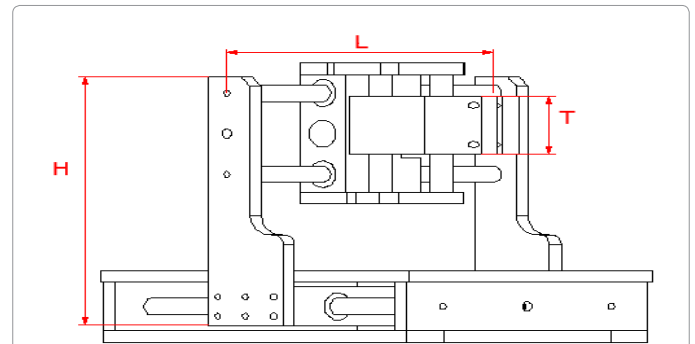


Figure 5: Optimal design variable of miniature engraving machine.

Levels	Factors		
	L/mm	T/mm	H/mm
1	262	51	240
2	272	61	250
3	282	71	260
4	292	81	270

Table 2: Factors and levels of orthogonal experiment design.

guides is 272 mm, the initial thickness of the spindle component is 61mm and the initial height of the uprights is 260 mm.

Determine the optimal design scheme

Based on the fact that the design variables are a series of discrete variable values, it is inevitable to make a large number of the comparisons and analysis of designs in order to obtain an optimal combination of design parameters. Therefore, this paper introduces the orthogonal experiment method to reduce the number of experiments. According to the theory, three design variables of multi-objective optimization are taken as the factors of orthogonal experiment. Then the orthogonal table of 4 levels and 3 factors is shown in Table 2, considering the allowed range of variable values.

For orthogonal experimental design scheme of Table 2, $L_{16}(4^3) = 16$ times of the finite element numerical simulations which are simulating the static structural analysis and modal analysis are expanded, and the design variables and the results of simulation experiments are shown in Tables 3,5 and 7.

Obtaining the Optimal Solution based on Grey Relational Analysis

In this paper, for the orthogonal experiments, 4 levels and 3 factors, have been used, a total of 16 times simulation experiments have been carried out, while the actual parameter combination has 64 kinds, so the other of 48 kinds of schemes are unknown. This constitutes a gray system which contains both known information and uncertain information, so it is difficult to obtain the optimal solution directly. Grey relational analysis is a method to measure correlation between factors according to the degrees of similarity and dissimilarity of the development trend between factors. Fortunately, this method is just to solve such problem of multi-objective optimization. Thus, grey relational analysis is adopted as the method to obtain the optimal solution.

Grey correlation analysis

According to the grey correlation analysis method, the original

Order	Frequency/HZ	Mode of vibration
1	166.23	Spindle component and guides bobbing up and down
2	184.77	Spindle component and workbench twisting
3	191.95	Spindle component swing back and forth
4	273.08	Uprights and workbench twisting

Table 1: The first 4 modal of the original miniature engraving machine.

Test number	Test factors			Test results			
	L/mm	T/mm	H/mm	Mass M/kg	Maximum deformation δ /mm	Maximum stress σ /Mpa	First-order natural frequency f /Hz
1	262	51	240	10.737	0.12546	12.461	167.63
2	262	61	250	11.006	0.13492	11.856	162.54
3	262	71	260	11.321	0.1409	13.679	158.29
4	262	81	270	11.615	0.1501	14.078	154.76
5	272	51	250	10.87	0.14631	12.725	173.81
6	272	61	240	11.102	0.13816	12.504	169.16
7	272	71	270	11.456	0.16538	13.531	160.73
8	272	81	260	11.69	0.15639	13.783	156.05
9	282	51	260	11.002	0.16344	12.498	168.61
10	282	61	270	11.293	0.17303	13.068	163.2
11	282	71	240	11.467	0.14758	12.519	159.34
12	282	81	250	11.761	0.15862	13.106	152.12
13	292	51	270	11.133	0.18139	12.731	165.56
14	292	61	260	11.364	0.17174	12.542	160.66
15	292	71	250	11.598	0.1635	12.373	154.31
16	292	81	240	11.832	0.16202	12.54	148.6

Table 3: Simulation results of engraving machine.

Number	Weight	Maximum deformation	Maximum stress	First-order natural frequency
1	1	1	0.647436	0.671014
2	0.670545	0.747228	1	0.527958
3	0.483871	0.644281	0.378664	0.448178
4	0.384076	0.531603	0.333333	0.398199
5	0.804555	0.572877	0.561111	1
6	0.6	0.687692	0.631609	0.730513
7	0.432294	0.411947	0.39878	0.490753
8	0.364878	0.474828	0.365701	0.415116
9	0.673846	0.424066	0.633771	0.707947
10	0.496149	0.370226	0.478261	0.542968
11	0.428571	0.558351	0.626268	0.465559
12	0.348393	0.457505	0.470563	0.367546
13	0.580286	0.333333	0.559416	0.604411
14	0.466156	0.376658	0.618253	0.48942
15	0.388711	0.42368	0.682432	0.392618
16	0.333333	0.433398	0.618942	0.333333

Table 4: Grey relational coefficient of objective function.

data of the orthogonal simulation results of engraving machine are converted to matrix X listed as follow:

$$X = \begin{bmatrix} M_1 & \sigma_1 & \delta_1 & f_1 \\ M_2 & \sigma_2 & \delta_2 & f_2 \\ \vdots & \vdots & \vdots & \vdots \\ M_{16} & \sigma_{16} & \delta_{16} & f_{16} \end{bmatrix} \quad (1)$$

To facilitate relational analysis, all the indicator values for engraving machine simulation results should be dimensionless normalized, and the processing methods are listed as follows:

(1) For the indicator (the first-order natural frequency) whose value should be bigger enough, its values can be updated by the following equation:

$$r_{i,4} = \frac{f_i - \min(f_1, f_2, \dots, f_{16})}{\max(f_1, f_2, \dots, f_{16}) - \min(f_1, f_2, \dots, f_{16})} \quad (2)$$

(2) For the indicators (the quality, maximum stress and

maximum deformation) whose value should be smaller enough, their values can be updated by the following equation:

$$r_{i,j} = \frac{\max(x_{1,j}, x_{2,j}, \dots, x_{16,j}) - x_{i,j}}{\max(x_{1,j}, x_{2,j}, \dots, x_{16,j}) - \min(x_{1,j}, x_{2,j}, \dots, x_{16,j})} \quad (3)$$

Where, $i = 1, 2, \dots, 16$, $j = 1, 2, 3$, and $x_{i,1}, x_{i,2}, x_{i,3}$ are respectively represented to M_i, σ_i, δ_i .

The new matrix of indicator values is generated as follow:

$$R = \begin{bmatrix} r_{1,1} & r_{1,2} & r_{1,3} & r_{1,4} \\ r_{2,1} & r_{2,2} & r_{2,3} & r_{2,4} \\ \vdots & \vdots & \vdots & \vdots \\ r_{16,1} & r_{16,2} & r_{16,3} & r_{16,4} \end{bmatrix} \quad (4)$$

Considering the 16 simulation schemes of engraving machine is related to comparison, an ideal reference scheme is firstly constructed which is denoted as follow:

Test number	Test factors			Value of comprehensive targets
	L/mm	T/mm	H/mm	
1	262	51	240	0.86369
2	262	61	250	0.723255
3	262	71	260	0.487773
4	262	81	270	0.406258
5	272	51	250	0.74862
6	272	61	240	0.649963
7	272	71	270	0.433213
8	272	81	260	0.39708
9	282	51	260	0.622695
10	282	61	270	0.47675
11	282	71	240	0.501464
12	282	81	250	0.39848
13	292	51	270	0.531547
14	292	61	260	0.483328
15	292	71	250	0.455231
16	292	81	240	0.410468

Table 5: Correlational degree of objective function.

L/mm	Degree of correlation	T/mm	Degree of correlation	D/mm	Degree of correlation
262	0.620244	51	0.691638	240	0.606396
272	0.557219	61	0.583324	250	0.581396
282	0.499847	71	0.46942	260	0.497719
292	0.470143	81	0.403072	270	0.461942

Table 6: Average correlational degree of design variables.

	M/kg	δ/mm	σ/Mpa	f/Hz	η
Original	11.162	0.15575	12.889	166.23	0.529151
Optimization	10.78	0.13292	11.52	177.89	0.86369
Rate of change	-3.422%	-14.658%	-10.621%	+7.014%	+63.22%

Table 7: Comparison between before and after optimization.

$$S^0 = [s_1^0, s_2^0, s_3^0, s_4^0] \quad (5)$$

Where, $s_j^0 = \max(r_{1,j}, r_{2,j}, \dots, r_{16,j})$, $j = 1, 2, 3, 4$, which means four evaluation indexes in matrix S^0 are the maximum values of the corresponding evaluation indexes of all schemes and it is used as the ideal scheme for standard. On this basis, taking the ideal scheme as the reference sequence, and taking the 16 schemes, respectively, as comparison sequence. The degree of closing to each other in two sequences usually can be described by the correlation coefficient ξ , which can be generated by the following equation:

$$\xi_{i,j} = \frac{\min_j \min_i |s_j^0 - r_{i,j}| + \varphi \max_i \max_j |s_j^0 - r_{i,j}|}{|s_j^0 - r_{i,j}| + \varphi \max_i \max_j |s_j^0 - r_{i,j}|} \quad (6)$$

Where $i = 1, 2, \dots, 16$, $j = 1, 2, 3, 4$, and $\xi_{i,j}$ is the correlation coefficient between the i -th comparison sequence and the j -th evaluation indexes of S^0 , and φ , which is an independently and uniformly distributed random variable within the range of $[0,1]$, is taken as 0.5 in this paper. Thus the gray correlation coefficient matrix about all simulation experiment schemes of engraving machine can be obtained and the new matrix E is given as follow:

$$E = \begin{bmatrix} \xi_{1,1} & \xi_{1,2} & \xi_{1,3} & \xi_{1,4} \\ \xi_{2,1} & \xi_{2,2} & \xi_{2,3} & \xi_{2,4} \\ \vdots & \vdots & \vdots & \vdots \\ \xi_{16,1} & \xi_{16,2} & \xi_{16,3} & \xi_{16,4} \end{bmatrix} \quad (7)$$

Assuming that the weight coefficients of the quality, maximum stress, maximum deformation and the first-order natural frequency about engraving machine are $\lambda_M, \lambda_\sigma, \lambda_\delta, \lambda_f$ respectively, so the degree of correlation about the i -th simulation experiment scheme with respect

to the ideal scheme is:

$$\eta_i = \lambda_M \xi_{i,1} + \lambda_\sigma \xi_{i,2} + \lambda_\delta \xi_{i,3} + \lambda_f \xi_{i,4} \quad (8)$$

Determining the objective function

The simulation results shown in Table 3 were calculated by using the method of gray correlation coefficients according to the formula (1)~(6), and the results are shown in Table 4.

In the process of multi-objective optimization about engraving machine, minimizing the maximum deformation and stress as well as improving the first-order natural frequency as much as possible are the basic requirements of optimizing the machining precision and working stability. However, lightening the weight of the engraving machine exert a negative effect on static and dynamic performance. The solution to this problem is to impart the weight coefficient of the engraving machine quality relatively larger. All the weight coefficients are set to $\lambda_M = 0.4, \lambda_\sigma = 0.2, \lambda_\delta = 0.2, \lambda_f = 0.2$ respectively. Then, all the values of comprehensive targets are shown in Table 5 by taking all the weight coefficients into Formula (8).

From the grey correlation analysis method, the greater the degree of correlation, the optimal goals are closer to the truly optimal value. The average degrees of correlation of design variable parameters of each level are shown in Table 6. From Table 6 we can see that the optimal design variables respectively are $L=262$ mm, $T=51$ mm, $H=240$ mm, and the optimal combination is $L_1T_1H_1$.

Experiment Validation and Discussion

On the basis of the result that the optimal combination is $L_1T_1H_1$, second modeling and finite element analysis of miniature engraving machine are implemented, and the comparison of each objective function between the original and after the optimization design is shown in Table 7. The result indicates that after the optimization

design, the mass has reduced 3.422%, the maximum deformation has reduced 14.658%, the maximum stress has reduced 10.621% and the first-order natural frequency has increased 7.014%, simultaneously. The comprehensive performance of static and dynamic have been highly improved. The physical model of miniature engraving machine according to the scheme after optimization design has been produced as shown in Figure 6. The stability of engraving machine is good and the machining precision is also meeting the design requirement. One of products produced by this engraving machine is shown in Figure 7.

Conclusion

This paper proposed a method of optimization design based on the orthogonal experiment design and grey correlation analysis. Then the optimization design of a miniature engraving machine has been realized by using this method. The main conclusions are as follow:

(1) This paper successfully combined the orthogonal experiment design and grey correlation analysis to apply to the multi-objective optimization design of miniature engraving machine, it has expanded the areas of application of these methods and showed the superiority of this method.

(2) In order to solve the conflict problem between improving the comprehensive performance and lightweight design, the weight coefficient of the mass is set to the largest so it can significantly improve the static and dynamic performance and obviously increase the first order natural frequency under the premise of controlling the mass of engraving machine.

(3) In the process of optimization design for miniature engraving machine, the orthogonal experiment method reduced the number of simulation experiment and the grey correlation analysis method solved the optimal combination of design parameters according to the results of simulation experiments. It has important theoretical significance and engineering application value in the field of decreasing the cost of the design of miniature engraving machine and increasing the comprehensive performance of static and dynamic.

(4) This adaptable and efficient method of optimization design proposed by this paper can be applied not only on the miniature engraving machine but also on other structures, even large structures. It can realize structural lightweight, reduce the manufacturing costs and further improve the market competitiveness of products.

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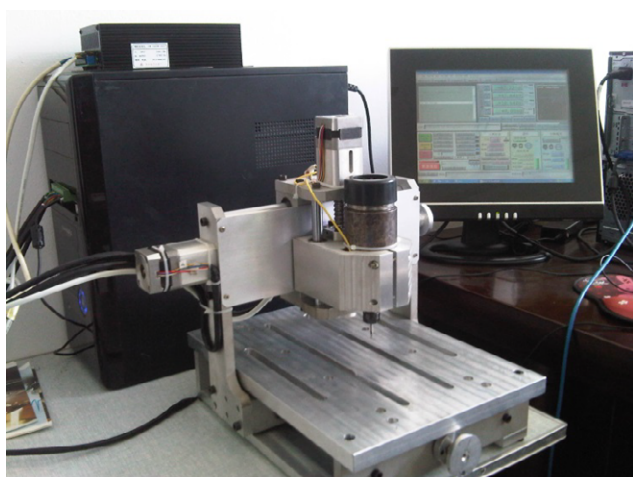


Figure 6: The miniature engraving machine after optimization design.



(a) Original picture of school badge



(b) Processed school badge

Figure 7: School badge processing.

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