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RESEARCH ARTICLE

Analysis of Crucial Factors Affecting Contact Force of PCB Spring Terminals Based on Simulation and Rank Correlation

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ABSTRACT A PCB spring terminal is a common type of connector found on the printed circuit board of electronic devices. Contact force is a crucial performance metric of this component that directly affects the product's dependability. In actual production, the contact force is unstable, and the influencing factors are unknown, whereas conventional experimental research is restricted to costly and error-prone trial-and-error procedures. In this study, finite element simulation technology and Spearman rank correlation analysis are combined to determine the crucial factors controlling the contact force of the PCB spring terminals in the structural design parameters and the plating related parameters. The validity of the results is confirmed by the measured data. The results indicate that the thickness of the spring terminal is the most significant factor in controlling the contact force. According to the conclusion, the company has re-established the inspection standard and resolved production problems. This case shows that the combination of finite element simulation and correlation analysis can be used to find the most important design parameters of such components quickly, accurately, and cheaply.

INDEX TERMS Electronic connector, design method, FEM analysis, Spearman rank correlation, contact force.

I. INTRODUCTION

A PCB spring terminal is a surface-mountable internal connector with a single contact that is applicable to all industries, all sorts of small printed circuit boards, and has multiple functions, including electrical connection, antenna feed, equipment grounding, or shielding. Contact force is one of the crucial indicators of spring terminals, which is closely related to the quality of signal transmission, as well as product life and stability. It is usually required to fall within a narrow range, and this range is related to the dimensions of the terminal structure. The smaller the terminal size, the narrower the contact force range. In this study, the contact force of the spring terminal is required to be in the range of $0.10 \sim 0.35$ N. In the production process of the product, the contact force performance is unstable, the influencing factors are unknown, and the control is inconvenient. Manufacturers have conducted a lot of experimental research, but the fine structure leads to large experimental errors and high costs. In addition, because the direction of experiments is unclear, manufacturers can only blindly try and make mistakes, which is extremely inefficient. In this study, a systematic method for determining the crucial influencing factors of the contact force with high efficiency, low cost, and high precision was developed to solve actual production problems based on finite element simulation technology and Spearman rank correlation analysis.

For the design and research of such products, IBM's Tom Macek and New York University's James M. Pitarresi [1] proposed that a connector design that meets all of the requirements of a particular electronic packaging application is becoming increasingly difficult to obtain by conventional "trial-and-error" analysis techniques. A more practical and dependable approach is the use of structural optimization analysis methods. In the process of structural optimization, as the products become more and more complex and

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sophisticated, it becomes more and more difficult to solve the analytical solution in the theoretical calculation. In general, numerical solutions based on the finite element method are the preferred method. Numerous studies have utilized the technology of finite element simulation to design and study such products [2], [3], [4], [5], [6], [7], [8]. These studies identify the types of parameters that can affect the contact force of spring terminals and use a variety of mathematical techniques to determine the optimal parameter combination that meets specific design requirements. But there is no study that measures how much different process parameters affect the contact force and shows which process parameters should be controlled the most.

More than ten structural design and plating treatment parameters are among the process factors that may influence the contact force of PCB spring terminals in this study. Academic research seeks to identify all the variables that influence the observed object and conduct a thorough analysis of these variables, whereas manufacturers prefer to allocate resources to the fundamental variables that have the greatest impact on contact force. In addition, although finite element simulation technology effectively shortens the product design cycle and improves the efficiency of product optimization, the computational cost of finite element analysis becomes a concern when a product has too many input parameters. Therefore, it is necessary to prioritize the importance of each input parameter to a specific indicator, and correlation analysis is the way to solve this problem. The purpose of correlation analysis is to determine whether there is an association between variables and to evaluate the strength of this association. Classic methods for correlation analysis include the Spearson product-moment correlation and the Spearman rank correlation. The former calculates the correlation coefficient between variables for linear, continuous, and normally distributed data using the actual value of the data [9], [10], while the latter is not limited to these conditions and uses the data's rank instead. Studies [11] show that Spearman rank correlation is more flexible, can handle more unusual data, and is thought to be a more accurate method.

In this study, to address the problems of unstable contact force and unclear influencing factors in the actual production process of the PCB spring terminals, the Spearman rank correlation method was selected in conjunction with the finite element simulation technology to investigate the impact of product structure design parameters and plating-related parameters on the contact force, identify the key parameters among them, and discuss how the key parameters affect the contact force. The research results can help manufacturers solve their contact force problems in a targeted and low-cost way. They can also give them ideas and ways to figure out the most important design and manufacturing factors for similar connector products.

Different from previous scattered and inference methods based on experience and limited test data, this paper proposes a systematic, reasonably predictive method, that can be used to quickly, accurately, and cost-effectively identify critical designs factors among numerous correlated variables.

II. FINITE ELEMENT SIMULATION

The appearance and dimensions of the PCB spring terminals are depicted in Figure 1. Table 1 displays the material parameters of the SUS301 stainless steel spring terminal and the Ni surface plating. The bilinear isotropic strengthening model is used to simulate the elastic-plastic constitutive relationship of the material. The tangent modulus of the model is 159 MPa, and the stress-strain response curve is shown in Figure 2.

TABLE 1. Materials parameters.

Material	Elastic Modulus (GPa)	Poisson's ratio	Yield Strength (MPa)
Base	153	0.34	1370
Plating	207	0.31	59

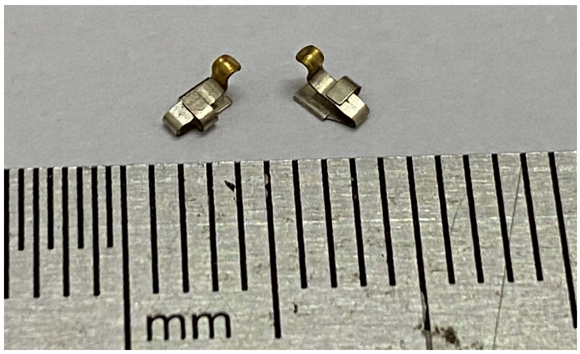

FIGURE 1. Physical view of PCB spring terminals.

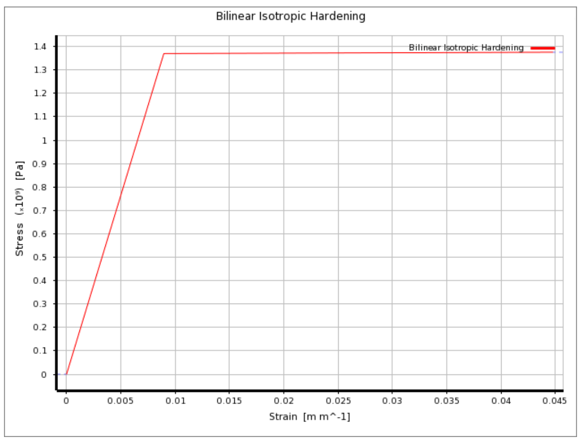

FIGURE 2. Material stress-strain relationship defined by bilinear isotropic hardening model.

For the spring terminal with plating, the primary connection between the base material and the plating is a mechanical bond. Under load, the material's elastic properties are reflected by the total elastic modulus of the terminal material and plating material. Equation (1) shows the exhaustive method for calculating elastic modulus used in this study.

$$E = E_{steel}V_{steel} + E_{Ni}V_{Ni} \quad (1)$$

Here, E_i is the integrated elastic modulus of the spring terminal with plating; E_{steel} is the elastic modulus of the base material stainless steel; V_{steel} is the volume fraction of stainless steel; E_{Ni} is the elastic modulus of the plating material Ni; V_{Ni} is the volume fraction of Ni.

The numerical simulation was implemented using the widely used commercial finite element analysis software ANSYS. Figure 3 depicts the finite element model used to analyze the contact force of the spring terminal. The element constituting the finite element model is Solid186, a high-order 3D solid element defined by 20 nodes, which supports plasticity, stress hardening, and large deformation. It should be noted that: (1) in order to improve the accuracy and convergence of the numerical calculation, appropriate simplifications were made, and non-essential parts of the structure were eliminated. (2) It is reasonable to assume that the contact object corresponding to the terminal is a plate with infinite stiffness, which can achieve numerical convergence without sacrificing accuracy. (3) Only the contact surface of the rigid body plate forms a mesh. The rest of the plate does not contribute to the meshing.

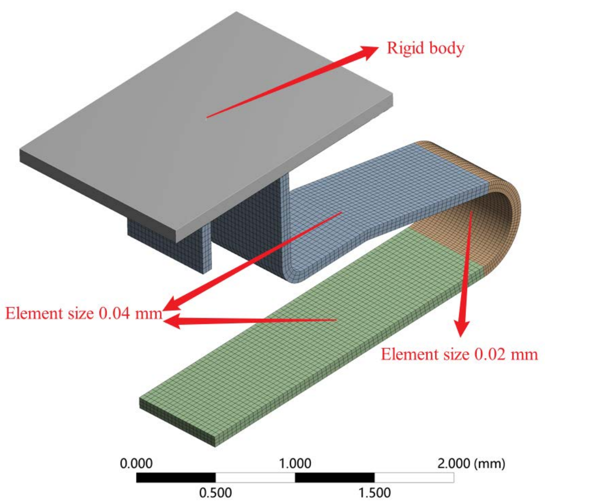

FIGURE 3. Finite element model for contact force analysis of PCB spring terminal.

The friction contact is chosen for the terminal and its counterpart, and the friction coefficient is 0.15. For the contact algorithm, the augmented Lagrange method is chosen, while Gaussian point detection is chosen for the detection method. The contact interface is configured as an adaptive touch to prevent model vibration.

The model's constraint and load conditions are depicted in Figure 4. To simulate the situation after the spring terminal has been mounted, the fixed support constraint is applied to the bottom of the spring terminal. To simulate the maximum deflection working condition specified in the terminal design drawing, a vertical downward displacement load of 0.81 mm is applied to the lower surface of the terminal counterpart. This analysis utilizes the structural static analysis system of the software. To ensure the convergence of the calculation and the precision of the results, it is necessary to activate the weak spring and large deformation switches in the software. In the spring terminal model, the reaction force caused by the displacement load of the corresponding object is taken as the contact force of the terminal after solution.

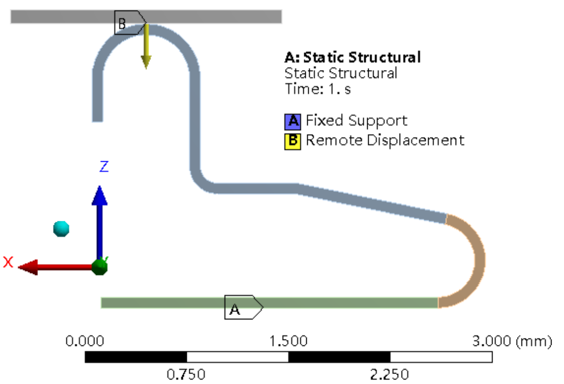

FIGURE 4. Constraints and loads of the PCB spring terminal model during simulation.

III. EXPERIMENT

Using a computer-controlled tensile testing machine, the contact force of PCB spring terminals in a specified deflection state was measured. Figure 5 depicts the experimental device and sample loading close-up view.

The experimental test objects include the spring terminal without plating and the spring terminal with plating. In each category, five samples were chosen for contact force testing, and each sample was repeated five times. Repeated testing can increase the reliability of the data, while the stability of the data can be used to determine whether plastic deformation accumulation has occurred under the test displacement conditions. Figure 6 depicts the results of contact force tests conducted on unplated and plated spring terminals, and the distribution of data points reveals the reliability of the results.

It can be seen from the test results that: (1) the repeated test data of the same sample are relatively stable, indicating that under the condition of test displacement, the material does not have plastic accumulation and leads to elastic attenuation. (2) There are certain fluctuations in the test data of different samples of similar objects, which reflect the problem of enterprises' unstable product contact forces. (3) The contact force of spring terminals that have been plated is greater than that of spring terminals that have not been plated.

IV. CORRELATION ANALYSIS

Correlation analysis is an application technology that identifies the existence of a relationship between objects and quantifies the degree of correlation. The correlation coefficient between parameters is its key metric. Figure 7 illustrates the correlation coefficient calculation process.

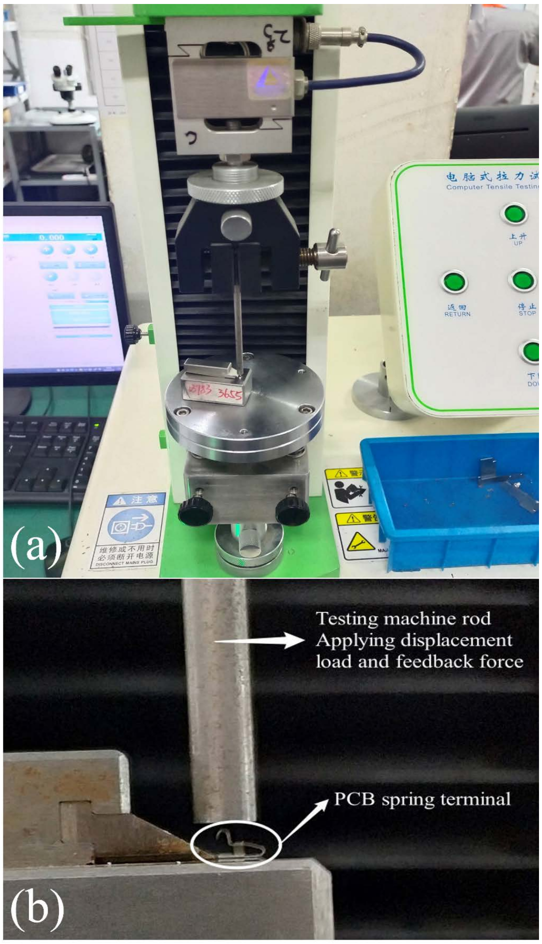

FIGURE 5. The experimental test instrument for contact force of PCB spring terminal (a) and the sample mounting details (b).

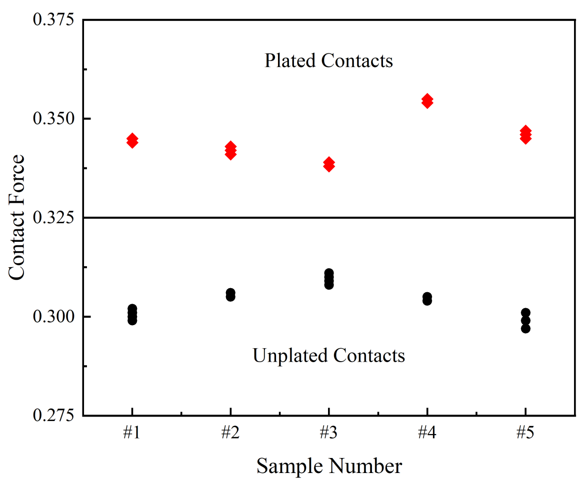

FIGURE 6. Experimental test results of contact force of PCB spring terminals.

In this study, the contact force was chosen as the output parameter, and the input parameters included structural design parameters and plating correlation parameters. Figure 8 depicts the structural design parameters, and the

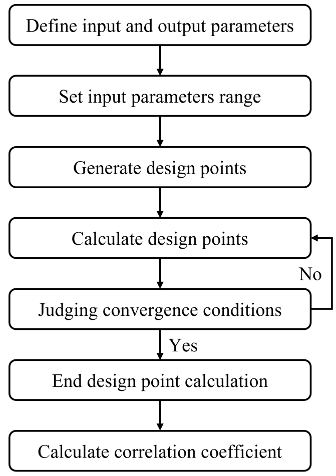

FIGURE 7. Correlation coefficient calculation flow chart.

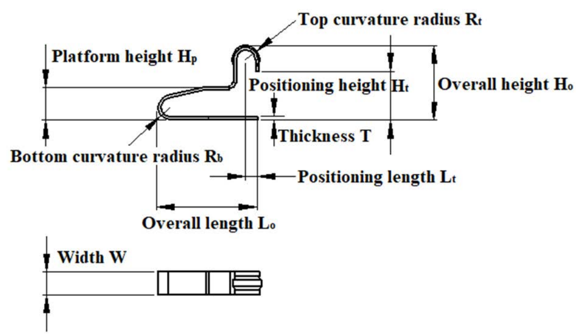

FIGURE 8. Schematic diagram of structural design parameters of PCB spring terminal.

TABLE 2. Analysis parameters and ranges.

Analysis Parameters		Parameter Range
Structural design parameters	T	0.080 ± 0.005 mm
	W	0.650 ± 0.05 mm
	H_p	0.920 ± 0.1 mm
	R_b	0.350 ± 0.05 mm
	R_t	0.400 ± 0.05 mm
	H_t	1.370 ± 0.1 mm
	L_t	0.330 ± 0.1 mm
Plating related parameters	ΔT	$0.080 \sim 0.090$ mm
	ΔW	$0.650 \sim 0.660$ mm
	ΔE_i	$153000 \sim 159727$ MPa

plating correlation parameters account for changes in plating thickness, width, and integrated elastic modulus, which are represented by ΔT, ΔW, and ΔE_i, respectively. Each input parameter's research scope is detailed in Table 2. The range of input structural design parameters is determined by the product design tolerance. The input range of plating correlation parameters is based on the minimum and maximum values of the corresponding parameters of the spring terminal with a plating thickness of between 0 μm and 5 μm.

In generating design points, the Latin Hypercube Sampling (LHS) method was used to extract design points within the parameter input range. Based on the extracted design points, contact force calculations were performed using a validated simulation process. During the calculation, it is determined that convergence has occurred when the average precision of the results reaches 0.01 and the precision of the standard deviation reaches 0.02. Figure 9 shows the results of the calculations for design points that meet convergence conditions as a scatter matrix.

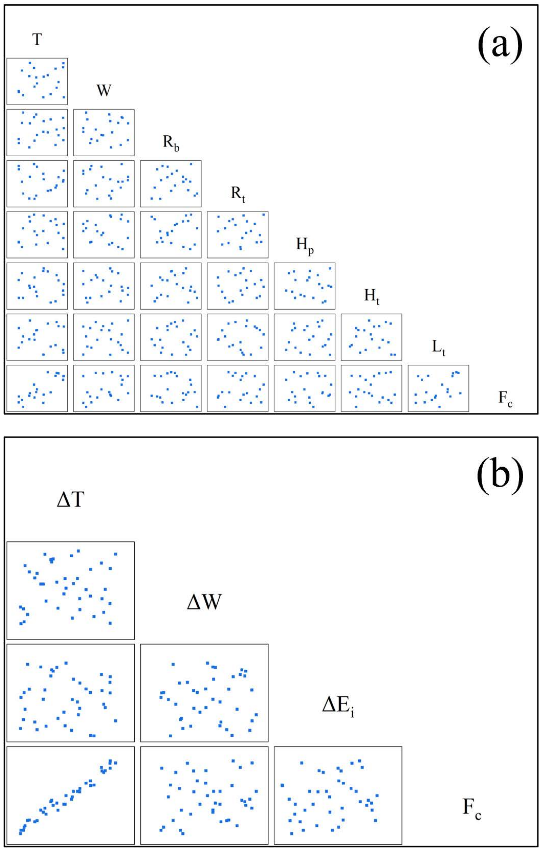

FIGURE 9. The scatter matrix diagram to express the design point calculation results of structural design parameters (a) and plating related parameters (b).

Figure 9 depicts the relationship between the parameters in the calculation results of the design point via scatter data, but most of the data is scattered, making it impossible to measure the correlation between the parameters with precision. Based on these results, the correlation coefficients of different parameter pairs were calculated according to Spearman's rank correlation theory. By comparing the correlation coefficients, the degree of association between each parameter and a specific indicator can be obtained. The Equation (2) illustrates the calculation method for the Spearman rank correlation coefficient [12].

$$r_s = \frac{\sum_i^n \left(R_i - \bar{R}\right)\left(S_i - \bar{S}\right)}{\sqrt{\sum_i^n \left(R_i - \bar{R}\right)^2}\sqrt{\sum_i^n \left(S_i - \bar{S}\right)^2}} \tag{2}$$

where:

R_i: rank of x_i within the set of observations $\lfloor x_1 x_2 \cdots x_n \rfloor^T$.
S_i: rank of y_i within the set of observations $\lfloor y_1 y_2 \cdots y_n \rfloor^T$.
$\bar{R}$,$\bar{S}$: average ranks of a R_i and S_i respectively.

To determine the statistical significance of the calculated results, it is necessary to test the significance of the correlation coefficient. The t-test [13] is used to verify the hypothesis under the assumption that there is no correlation between the variables, i.e., the correlation coefficient is 0. The calculation method for data with a sample size of n is shown in Equation (3):

$$t = r_s \sqrt{\frac{n-2}{1-r_s^2}} \tag{3}$$

The distribution of t is similar to the student's t distribution of degree of freedom $v = n - 2$, and the cumulative distribution function of the distribution can be expressed as Equation (4) [14].

$$A\left(t \mid v\right) = \frac{1}{\sqrt{v}B\left(\frac{1}{2}, \frac{v}{2}\right)} \int_{-t}^{t} \left(1 + \frac{x^2}{v}\right)^{-\frac{v+1}{2}} dx \tag{4}$$

where:

$B\left(\cdots\right)$: complete Bate function.

The probability that the original hypothesis is true is given by $1 - A\left(t \mid v\right)$. When $1 - A\left(t \mid v\right)$ exceeds a significant level, such as 0.05, it can be inferred that the original hypothesis is true and the correlation coefficient results are not obvious; when $1 - A\left(t \mid v\right)$ is lower than the significance level, it can be inferred that the original hypothesis is not correct, and the correlation coefficient results are significant.

V. RESULTS AND DISCUSSION

In order to verify the accuracy of the simulation analysis, the maximum simulated contact forces of the spring contact should be first compared with the corresponding measured values under experimental conditions. Table 3 lists the maximum contact forces of the spring contact subjected to specified displacements based on both simulations and measurements. It shows that numerical results agree well with measurements, whereas the associated errors are still within the acceptable margin.

TABLE 3. Contact force of PCB spring terminals based on simulation and measurement and their comparison results.

Object	Measurement average (N)	Simulation value (N)	Error (%)
Unplated	0.303	0.308	1.7
Plated	0.345	0.356	3.2

A. PARAMETER CORRELATION ANALYSIS RESULTS

The correlation matrix diagram is used to display the correlation analysis's calculation results. Figure 10 depicts the

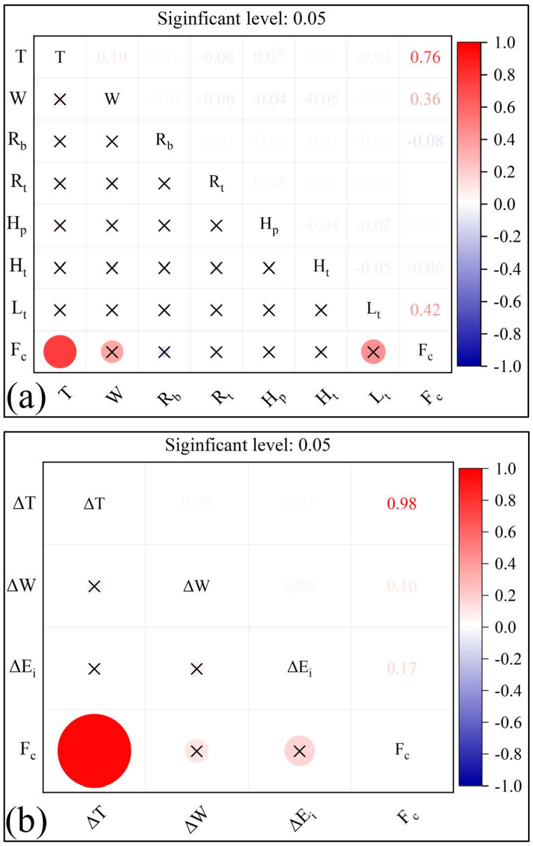

FIGURE 10. Correlation matrix of structural design parameters of PCB spring terminals (a) and correlation matrix of plating related parameters (b).

correlation matrix diagram between the various spring terminal parameters, where (a) represents the correlation between the structural design parameters and the contact force, and (b) represents the correlation between the plating correlation parameters and the contact force. Using circles of varying sizes and colors, the lower left portion of the figure illustrates the relationship between each parameter. The greater the size of the circular area, the more prominent the color and the stronger the correlation. The section in the upper right corner displays the correlation coefficient between the parameters. The value is more apparent, the greater its absolute value. At the same time, all correlation coefficients are tested for significance at a level of significance of 0.05. If the results are insignificant, they are denoted with a ×.

Figure 10(a) demonstrates that, among the structural design parameters of the spring terminal, the thickness T, width W, and positioning length L_t have obvious correlations with the contact force F_c, and their respective correlation coefficients are 0.76, 0.36, and 0.42, respectively. However, according to the result of the significance test at the 0.05 level, only the correlation coefficient between T and F_c is significant. According to the interpretation of the correlation coefficient in the literature [15], there is a strong correlation between T and F_c within the scope of the study. As shown in Figure 10(b), the correlation coefficient between the plating-induced change in thickness and the contact force reaches 0.98, passing the significance test, indicating a strong correlation between the two variables within the scope of this study. The correlation coefficient between the change in width and the comprehensive elastic modulus and the contact force is not clear, and it failed the significance test, so it is likely that they do not have a clear relationship with the contact force.

B. PARAMETER SENSITIVITY ANALYSIS RESULTS

Through the correlation analysis, the parameters significantly related to the contact force of the spring terminal and their related strength are obtained. On this basis, further sensitivity analysis can be done. Sensitivity analysis is a technique for determining how different values of an independent variable affect the dependent variable under a given set of assumptions. By deciphering parameter sensitivity, it is possible to design for more reliable, better quality, or to reduce the cost of the manufacturing process while maintaining product reliability and quality.

The sensitivity based on the correlation coefficient adheres to the principle that the stronger the correlation between output parameters and particular input parameters, the more sensitive it is to changes in the input parameters. This sensitivity is a statistical sensitivity, namely the global sensitivity, which does not depend on the value of the input parameters because the sample point is in the entire space of the input parameters and all possible values of the input parameters are considered when assessing the sensitivity.

Figure 11 depicts a sensitivity map of the structural design parameters and plating-related parameters of the spring terminal, allowing the researcher to observe at a glance the influence of all input parameters on the output parameters. When increasing the input causes the output to increase, positive sensitivity is displayed, otherwise negative sensitivity is displayed. Figure 11(a) demonstrates that, among all structural design parameters, the thickness is the most sensitive with a value of 0.759. This demonstrates that, relative to other parameters, the thickness has the most impact on the contact force, and as the thickness increases, so does the contact force. Figure 11(b) demonstrates that the sensitivity of the contact force to the plating-caused thickness variation reaches 0.980, which is significantly greater than other parameters. This suggests that the effect of the plating on the contact force is almost entirely attributable to variations in thickness, while the effects of variations in width and integrated elastic modulus are negligible.

C. QUANTITATIVE ANALYSIS RESULTS OF THE CRUCIAL PARAMETER

The preceding analysis has obtained a qualitative judgment. The thickness of the spring terminal is the most critical factor affecting the contact force. The following quantitative analysis is used to determine the degree of influence of the thickness. Firstly, consider changing only the thickness value in the structural design. Figure 12 demonstrates that as the

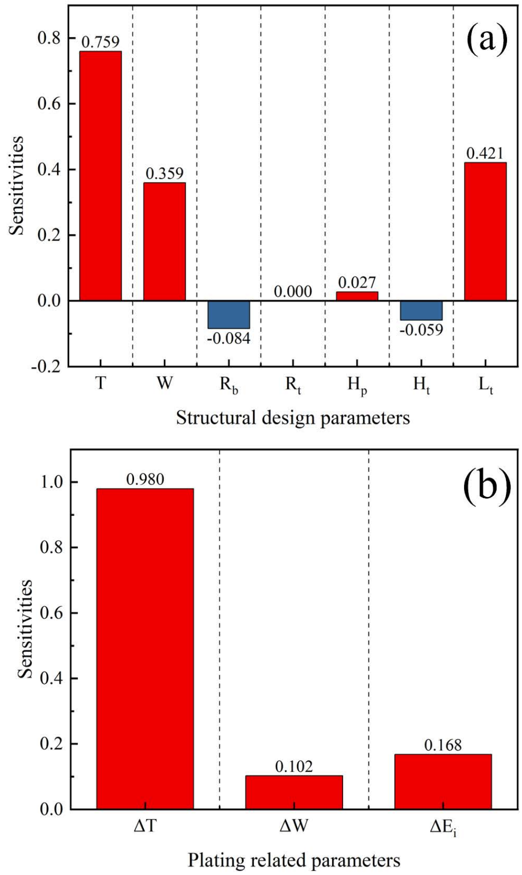

FIGURE 11. Sensitivity diagram of PCB spring terminal contact force to structural design parameters (a) and to plating related parameters (b).

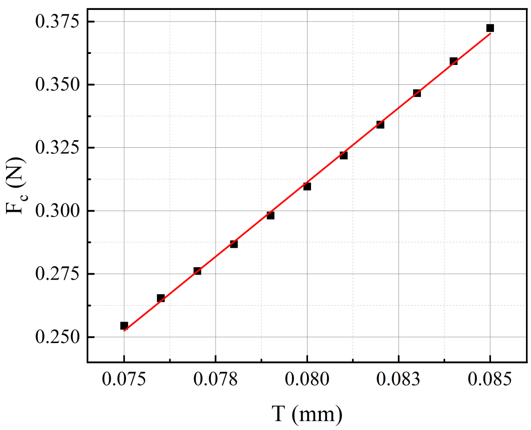

FIGURE 12. Single factor relationship between contact force and thickness of PCB spring terminal.

thickness increases from 0.075 mm to 0.080 mm, the contact force increases from 0.254 N to 0.372 N, a 46% increase, and the growth relationship is linear.

Secondly, considering the effect of plating thickness, the plating will simultaneously alter the spring terminal's structural size and integrated elastic properties. Using the response surface method, the interactive effects of multiple parameters on the contact force were characterized. As illustrated

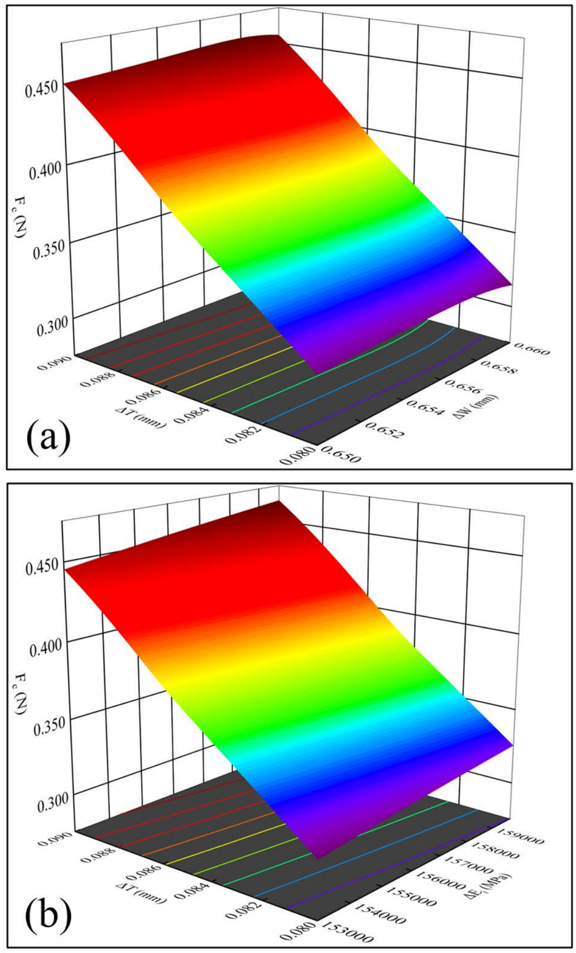

FIGURE 13. Response surface of contact force vs. thickness-width (a) and vs. thickness-integrated elastic modulus (b).

in Figure 13(a), as the thickness of the plating increases from 0 to 5 μm, the contact force increases by 46%, from 0.315N to 0.458N due to the combined effect of thickness and width. As shown in Figure 13(b), the combined effect of thickness and integrated elastic modulus increases the contact force by approximately 49%, from 0.311N to 0.465N. The response surface of the two can be viewed as a plane, and the contour projection can be viewed as a straight line. From the dimension of thickness, contact force increases significantly as thickness increases; from the dimensions of width and integrated elastic modulus, contact force does not change significantly with their increases. All of these results indicate that, in terms of the multidimensional effects caused by plating, the variation in thickness occupies an absolute leading position while the effects of other related parameters are minimal. This corresponds to the results of qualitative analysis, which proves that the results are accurate.

VI. CONCLUSION

A product design method that combines finite element simulation technology with correlation analysis method is proposed, which can determine the crucial design parameters of specific indicators simply, efficiently, and accurately. The method is successfully applied to real-world situations, and the key factors influencing the contact force of PCB spring terminals are analyzed. The thickness (including material thickness and plating thickness) is the most important factor in controlling the contact force, which is manifested in two ways. On the one hand, the correlation between thickness and contact force is the strongest. On the other hand, the contact force is most sensitive to variations in thickness. The contact force increases by approximately 50% when the thickness increases by only 0.01 millimeters. Therefore, it is recommended that all links and processes related to thickness in the design and production of similar products be strictly regulated.

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