Original Research Article

# Flip chip loader accuracy optimization design approach

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***Abstract:*** With the increasingly urgent demand for high-precision flip chip bonding machines in integrated circuit packaging technology, and in view of China's reliance on imported high-end equipment, this study proposes an accuracy optimization design method for flip chip bonding machines.Based on the multi-body system theory, the spatial error model of the flip chip bonding machine is established, which reveals the coupling relationship between the geometrical error of the moving parts and the overall bonding accuracy.Through the error sensitivity analysis by matrix differentiation method, the critical geometric error parameters(such as line displacement error, angular displacement error and guide verticality error)are identified, and the accuracy optimization design model aiming at the minimization of manufacturing cost is constructed by this method.Combined with the genetic algorithm, 15 line displacement error parameters are globally optimized, and the results show that the optimized tolerance assignments meet the bonding accuracy requirements(X, Y, Z direction accuracy is significantly improved)while expanding the acceptable error range and reducing the manufacturing cost, realizing the synergistic optimization of performance and cost.In addition, the angular displacement error and perpendicularity error are indirectly optimized through error parameter traceability and identification, which solves the problem of synergistic optimization of multi-measurement error.This study provides theoretical support and practical guidance for the design and manufacture of domestic high-precision flip chip loader.

***Keywords:*** Flip chip loader; Geometric error; Sensitivity analysis; Precision design

## 1. Introduction

With the rapid development of electronic technology, flip chip technology is more and more widely used in the field of integrated circuit packaging.With its excellent electrical and thermal properties and small shape factor, flip chip occupies an important position in many fields such as communication equipment, computer system and consumer electronics.As the key equipment of flip chip packaging process, the accuracy of flip chip loading machine directly determines the yield, reliability and manufacturing cost of flip chip.At present, the international market demand for high-performance, low-power, thin and light chips continues to grow, promoting the continuous progress of flip chip technology.Internationally renowned packaging equipment providers such as Switzerland Esec2100, Panasonic FCB3 and Toray FC3000 have launched high-precision flip chip loading machine, these devices in the 3σ range of accuracy up to ± 3μm - ± 12μm, bonding speed can reach thousands or even tens of thousands of chips per hour.However, China is still dependent on imports in the field of high-end flip chip loader, which not only increases the production cost of enterprises, but also seriously restricts the development of China's IC packaging industry[1].Therefore, it is of great practical significance to carry out the research on the optimal design method for the accuracy of flip chip loading machine and realize the localization of the equipment.

## 2. Modeling of spatial errors in flip chip bonding machines

### 2.1. Theoretical foundations of many-body systems

Multi-body system theory is an important tool for the study of complex mechanical systems,which adopts a unique description to clearly express the various factors affecting the mechanical system as well as the coupling relationship between the factors.The theory will be more than one rigid or flexible body through a specific connection to form a mechanical system with a certain motion relationship,for mechanical structure analysis,institutional motion control simulation and mechanical system error analysis provides a strong support.[2] In the flip chip loading machine,there are complex motion relations between the moving parts,and the theory of multi-body system can abstract these parts as individuals in the multi-body system,and by describing the correlation relations and motion characteristics between the individuals,it lays the foundation for establishing the spatial error model.

### 2.2. Structure analysis of flip chip bonding machine

Take the OCTOPUS-1000 flip chip bonding machine developed by an enterprise as an example,it is mainly composed of chip pretreatment module,chip transfer module and chip bonding module.The chip pre-processing module is responsible for chip positioning,stripping,flipping and other operations; the chip transfer module passes the pre-processed chip to the chip bonding module; the chip bonding module completes the alignment and bonding of the chip and the substrate.The motion structure of the bonding machine includes a bonding head system and a substrate wafer table.The bonding head system has multiple degrees of freedom,which can realize the movement and positioning of the chip in multiple directions; the substrate wafer table is used for the positioning of the substrate.In the bonding process,the relative motion accuracy of the bonding head system and the substrate wafer table directly affects the alignment accuracy of the chip and the substrate,which in turn affects the bonding accuracy.

### 2.3. Spatial error modeling process

Based on the multi-body system theory,the spatial error modeling of flip chip bonding machine is carried out.First,the geometric structure of the bonding machine is described,its complex motion structure is abstracted into a topological structure,and a low-order body array is used to describe the correlation relationship between the bodies.By establishing a right-handed right-angle Cartesian three-dimensional generalized coordinate system,sub-coordinate systems solidly associated with each body are established on each body,and the relative positions between sub-coordinate systems and their variations are defined by chi-square eigenmatrices,thus describing the relative positions and motion conditions between the bodies[3].Next,the neighboring body eigentransformation matrices are derived for the ideal case and the actual case.In the actual case,considering the manufacturing and installation errors of each moving body,there are six motion errors(three linear displacement errors and three angular displacement errors)for each moving body,as well as relative positional errors between the moving bodies(described by perpendicularity errors between the guideways or between the motion axes). Finally,the zero-level kinematic equations of the chip kinematic chain branch and the substrate kinematic chain branch in the actual case are established according to the position transfer principle between the bodies,and the spatial error model of the flip chip bonding machine is obtained by describing the relative errors of the two kinematic chain branches.The model reflects the relationship between the geometrical error of each moving part and the overall bonding error,which provides the basis for the subsequent accuracy analysis and optimized design.

## 3. Sensitivity analysis of spatial error in flip chip bonding machine

### 3.1. Establishment of sensitivity analysis model

According to the spatial error model of the flip chip bonding machine,the matrix differentiation method is used to establish a general model for error sensitivity analysis.The spatial error model is expressed as a function of the geometric error,the chip and substrate position coordinates and the motion axis position vector,and the function is expanded with a first-order Taylor series at the ideal value,ignoring the higher-order terms to obtain the error sensitivity analysis model.In the actual analysis,the chip and substrate bonding point positions are fixed,i.e.,the coordinate position vectors are set to be fixed values,and the focus is on the effect of geometric error on the overall spatial error[4].By calculating the effect of small fluctuations in the geometric error vector G on the spatial error E,the error sensitivity matrix S is obtained,and the elements in the matrix indicate the sensitivity of each geometric error to the spatial error.

### 3.2. Measurement of geometric error parameters

Agilent's 5529A dual-frequency laser interferometer was chosen to measure the geometric error parameters of the OCTOPUS-1000 flip-chip bonding machine.In the working area of the bonding machine,the middle section of each motion axis is selected as the measurement area,and 20 data acquisition points are set in the measurement range.In order to ensure the accuracy of the data,the motor dwell time at each data collection point position is 5s,and each geometric error value is repeated 5 times,and the average value is taken as the measurement result.Finally,34 geometric error data were obtained,and these data provided the basis for the subsequent sensitivity analysis.

### 3.3. Identification of critical geometric error parameters

According to the error sensitivity analysis model,the sensitivity of each geometric error parameter is calculated.The geometric error parameter sensitivity reflects the degree of change in the total spatial error when each geometric error element produces a small change.

When analyzing the sensitivity of each geometric error parameter,first calibrate the position of the midpoint of the chip bonding surface,the position of the midpoint of the substrate bonding surface,and the motion displacement of each axis of motion.Taking the bonding wafer center substrate as an example,the relevant position coordinates and motion displacement values are determined.It can be seen through the calculation that different geometric error parameters have different degrees of influence on the overall spatial error.In order to analyze the influence of each geometric error parameter more intuitively,it is normalized and the sensitivity coefficient is defined.By analyzing the sensitivity coefficients,the critical geometric error parameters that have a greater impact on the bonding accuracy of the flip chip bonding machine are identified[5].For example,11 critical geometric error parameters are identified in the direction,and a corresponding number of critical error parameters are also identified in the and direction,respectively.When carrying out the accuracy design,the focus should be on controlling the values of these critical geometric errors to improve the bonding accuracy.

## 4. Flip chip bonding machine accuracy optimization design

### 4.1. Traceability and identification of error parameters

The bonding accuracy of the flip chip bonding machine is the result of the coupling of errors on the functional surfaces of related parts.Based on the spatial error model,each error parameter in the model is traced back to the corresponding functional surface of the parts,and the correspondence between each individual error parameter and the accuracy of the flip chip bonding machine parts is established.For example,the line displacement error corresponds to the manufacturing accuracy of the scale,and the angular displacement error corresponds to the parallelism error in the vertical plane of the X1 guideway.Since the angular displacement error and perpendicularity error have different magnitudes from the line displacement error,they are not suitable for direct optimization in the same optimization model[6].Therefore,by analyzing the physical and geometric relationship that exists between them and the line displacement error,the angular displacement error and perpendicularity error are approximated using the line displacement error.As an example,according to the relationship between parallelism error and line displacement error in the perpendicular plane between two guide rails,the identification formula of angular displacement error and line displacement error is obtained.Similarly,the identification relationship between other angular displacement error and perpendicularity error and line displacement error is deduced,which facilitates the subsequent precision optimization design.

### 4.2. Accuracy optimization design model construction

According to the minimum cost method of tolerance assignment,the accuracy optimization design model of flip chip bonding machine is established.The objective function is cost-oriented,and the square inverse model is used,i.e.,where indicates the value of each geometric error parameter,and n is the number of design variables,and this study takes 15 items of line displacement errors as the design object,so n=15,which is the cost weighting coefficients of each design variable.The design variable is 15 items of line displacement error,i.e.

,is denoted.The determination of the weighting coefficient is combined with the results of the geometric error sensitivity analysis,and a larger weighting coefficient is set for the line displacement error associated with the key geometric error; a smaller weighting coefficient is set for the line displacement error with a smaller impact.For example,for,according to the sensitivity of the angular displacement error and perpendicularity error associated with it,determine its weight coefficient.For line displacement errors that are not directly related to angular displacement errors and perpendicularity errors,such as positioning errors,the weighting coefficients are determined by indirect means.Finally,the weighting coefficients are normalized so that the sum of the weighting coefficients is 1.The constraints include the overall accuracy constraint and the individual geometric error constraint.The overall accuracy constraints require that the accuracy in X,Y and Z directions meet the predetermined bonding accuracy of the flip chip bonding machine; the single geometric error constraints take the empirical design value as the lower limit and the overall bonding accuracy value as the upper limit,which ensures that the optimization results not only meet the accuracy requirements,but also have practical feasibility.

### 4.3. Accuracy optimization based on genetic algorithm

Genetic algorithm is a global optimization search algorithm that simulates the biological evolution process,which has the advantages of being simple and general,robust and suitable for parallel processing.In this study,MATLAB genetic algorithm and direct search toolbox GADS are used to carry out accuracy optimization design of flip chip bonding machine.First,according to the accuracy optimization design model,the M-file of the objective function is written in MATLAB to define the objective function to be optimized.Then,set up each option box of the graphical interface of the GA tool.Set the fitness function as the objective function written,and determine the number of variables as 15; set the variable constraints,including the constraint lower limit and upper limit; set the population parameters,such as the population type,size,creation function,and initial range; select the fitness scaling ratio,the selection operation method,the crossover operation method,and the variance operation method,and set the corresponding probability; and set the stopping condition parameters,such as the number of running generations and the time limit,stagnation algebra and adaptation limit,etc.After completing the parameter settings,run the genetic algorithm for optimization.After a certain number of runs,the algorithm stops and the optimization results are obtained.The optimization results include the optimized design values of each line displacement error,and the corresponding optimized values of angular displacement error and perpendicularity error are obtained by identifying the relationship between angular displacement error and perpendicularity error and line displacement error.

### 4.4. Analysis of optimization results

A comparative analysis of the optimized results is carried out,including the comparison of each single geometric accuracy and the overall accuracy comparison.In terms of the single geometric accuracy,the optimized design value of line displacement error obtained by genetic algorithm is compared with the traditional empirical design value,and it is found that the optimized value of line displacement error is enlarged to a different degree,and the weight coefficients of positioning error are embodied in the optimized design,and the assigned accuracy is more stringent.Meanwhile,by comparing the optimized values of angular displacement error and perpendicularity error with the empirical values,it is verified that the correctness of the identification relationship between angular displacement error and perpendicularity error and line displacement error is verified,and the width of the optimized tolerance band is also enlarged to different degrees.In terms of overall accuracy,the optimized geometric error values are substituted into the spatial error model,and the obtained overall accuracy meets the predetermined bonding accuracy requirements of the flip chip bonding machine.Compared with the overall accuracy obtained from the empirical design,the X-direction bonding accuracy is similar,and the Y-direction and Z-direction bonding accuracies have been greatly improved.This shows that this precision optimization design makes the cost and performance of the flip chip bonding machine better adjusted,and reduces the manufacturing cost and improves the cost-effectiveness of the equipment under the premise of guaranteeing the precision.

## 5. Conclusion

This study has carried out an in-depth research on the precision optimization design method of flip chip loading machine,and achieved the following main results:based on the multi-body system theory,a spatial error model of the flip chip bonding machine is established,which accurately reflects the relationship between the geometric error of each moving part and the overall bonding error,and provides an effective tool for the precision analysis and optimization design.The spatial error sensitivity analysis is carried out by matrix differentiation method,which identifies the key geometrical error parameters affecting the bonding accuracy and provides a key basis for the accuracy design,and the calculation of the sensitivity coefficients provides a scientific method for determining the weight coefficients in the accuracy optimization design model.The accuracy optimization design model is established and combined with genetic algorithm to optimize the geometric error parameters of flip chip bonding machine.The optimization results show that on the basis of meeting the bonding accuracy requirements,the range of each error is expanded,the manufacturing cost is reduced,and a better match between cost and performance is achieved.At the same time,the optimization of angular displacement error and perpendicularity error is indirectly realized through the optimization of line displacement error,which avoids the problems caused by the inconsistency of the gauge.

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