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Topological Optimization of R-θ Robot Structure Based on Homogenization Method

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Abstract: R-θ robot arm is an important part of the robot to achieve the function, low stiffness seriously affect the accuracy and efficiency of work, so the requirement of stiffness is higher. In order to improve the rigidity, this paper put the arm structure as the research object to optimize. First of all, the relationship between the total deformation of the joint arms and the wall thickness of the arms are analyzed, get the optimal wall thickness and improving the structure of the arm, a new arm structure model is established. On this basis, the topology optimization method based on homogenization method is used to optimize the arm structure and get the final optimal structure. Finally, verification and analysis are carried out on the arms of a single-arm R-θ robot. The results show that the combination of two optimization methods can not only effectively reduce the arm weight, but also better improve the natural frequency, thereby increasing the stiffness The model and analysis conclusion of this paper will provide theoretical support for the actual improvement of the motion performance of the robot.

1. Introduction

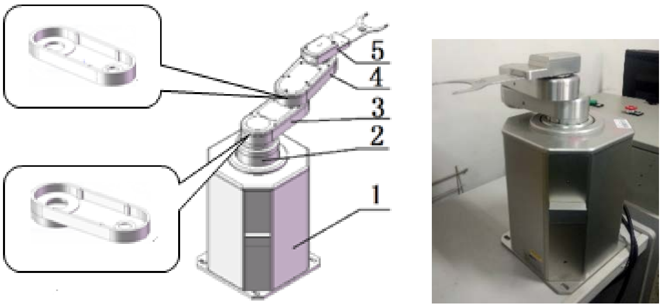
The R-θ type robot is the important equipment in the process of making the semiconductor material, and its working precision seriously affects the precision and performance of the semiconductor material. In the processing of semiconductor materials, R-θ type robot is mainly responsible for the wafer clamping, transmission and positioning work, it plays a vital role in the accuracy of the entire system. R-θ robot arm is an important component to achieve the function, the performance of the arm of the robot's working precision plays a vital role, when the big arm and forearm has very small deviation will affect the end of the positioning accuracy, even damage the silicon wafer[1]. In order to make the robot arm more stable at work, this paper optimizes the structure of the arm shell, reduces the total compliance value, and improves the rigidity of the arm shell and the system.

Structural optimization has three ways: size optimization, shape optimization and topology optimization. After the structural design has been completed, the effect of the size optimization and shape optimization is not obvious, the degree of change is limited[2]. Compared with the former two optimization methods, topology optimization can be more flexible and changeable to improve structure layout. Topology optimization is based on the requirements of performance objectives and constraint boundary, optimize the material distribution of optimization part. Topology optimization to display on the optimization of regional material distribution in density as a result, the high density material distribution area for the reserved area, used as structure; low density area for removal of the area, the area is designed for hole. Although the topology optimization process is complicated, but its flexible structure optimization layout, can make up for the deficiency of other traditional optimization methods.

At present, some domestic and foreign scholars have a lot of research on the vibration suppression of R-θ type robot[3-5], Mainly through optimization algorithm to optimize the trajectory precision so as to achieve the effect of vibration suppression. However, there is little research on the arm structure of R-θ robots, and they are all optimized for arm structure in a single way. KAWAMUTRA et al.[6] used the Lagrangian equation for dynamics modeling, the quality of the arms center is designed to be close to the center of rotation, make its moment of inertia small, to suppress vibration, Yan jieliu[7] to weight the inherent frequency as basis, to the end of the arm deformation as constraint conditions, to arm wall thickness as a variable to optimize the structure of arm, Albert Albers[8-9] et al. used ARMAR robotic arm as the research object, and optimized them by topology optimization method. Zhang Chuansi[10] for the purpose of vibration suppression, with the continuum topology optimization method for silicon wafer transfer robot for optimal design.

2. The model of the study object

The 3D model of R-θ type robot is drawn by studying the working principle and structure of R-θ robot. In the process of modeling, in order to avoid a large amount of calculation, will remove some rounded corners does not affect the results of modeling features, and then simplified model for finite element analysis. Finally, figure 1 shows the physical and 3D models of R-θ robots.



1.Engine base 2. Lifting and rotating parts 3.Big arm 4.Fore arm 5. End effector

Fig.1 R-θ robot

The end of the R-θ robot moves linearly at work, and the arms are rotated at one end as the center of rotation. This article mainly analyzes the static stiffness of the arm, so the arm can be simplified as a cantilever structure at rest. However, the arms and arms are shells, so the structure of the arm can be simplified as a square beam of equal cross-section as shown in Figure 2, of which A is the inner width of the arm shell, B is the total thickness of the arm shell, bi is the wall thickness variable of the arm, OYZ is the cross section coordinate system, and Y_C is the curved central axis.

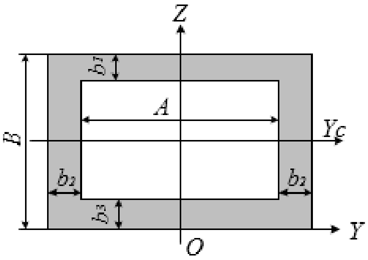


Fig.2 Diagram of the arm shell

When stationary, R-θ robot arm can be as a cantilever beam structure, one end fixed and the other part is a free state, the force can be simplified as shown in figure 3.

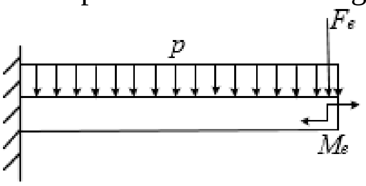


Fig.3 The stress diagram

In this paper, the weight of the arm shell is evenly distributed, expressed as the weight p, Fe is the equivalent force of the end of the arm shell, Me is the equivalent moment of the end of the arm shell, according to Figure 3 can get the total deformation δ for the end of the arm

$$\omega_0 = -\frac{M_e L^2}{2EI_{yc}} - \frac{F_e L^3}{3EI_{yc}} - \frac{pL^4}{8EI_{yc}}$$

$$\theta_0 = -\frac{M_e L}{E I_{yc}} - \frac{F_e L^2}{2 E I_{yc}} - \frac{p L^3}{6 E I_{yc}}$$

$$\delta = \omega_0 + L' \sin\theta_0 \quad (1)$$

In formula (1) ω_0——Deflection at the end of the arm;

θ_0—— The rotation Angle of the end of the arm;

δ—— The total deformation of the end of the arm;

I_{yc}—— The moment of inertia of the cross section of the arm relative to the Y_C axis;

S_e—— Sectional area of the arm;

L'—— The total length of the series arm;

E—— Material elastic modulus;

ρ—— Material density.

3. Theoretical Basis of Topology Optimization

The structure of the traditional optimization method is generally only optimize the wall thickness, the optimized structure is obtained according to the optimal wall thickness, but change is limited, and topology optimization can optimize the material density of regional layout, the low density area removed, designed as hole structure, to draw a new structure. In this paper, the natural frequency is used as the criterion, and two optimization methods are combined. The wall thickness of the arm is optimized first, then the topology is optimized according to the optimized structure, Finally, the optimal structure is obtained.

Topology optimization is based on the required performance objectives and constraint boundary to optimize the material distribution of the region to optimize. The goal of topology optimization is to find the best material allocation scheme for single or multi-load objects, can be divided into: continuum topology optimization and discrete structure topology optimization, and continuum topology optimization is widely used. In this paper, continuum topology optimization is adopted.

In this paper, in order to meet the arm shell material removal rate to improve the arm stiffness as constraint boundaries, so R-θ mathematical model of the robot arm is:

$$\begin{cases} \text{Find } \eta_i \ (i=1, \ \ldots\ldots, \ n) \\ \text{Min} F(\eta_i) \\ \text{s.t.} \int_\Omega \eta_i d\Omega \ll \alpha V \\ 0 \le \eta_i \le 1 \end{cases} \quad (2)$$

In formula (2) F——Arm deformation energy;

ηi——The pseudo density of the i-th unit;

n——The number of units;

α——The percentage of material removal;

V——Initial volume of arm;

Topology optimization using optimization algorithm for multiple iterations, when the result in a numerical convergence calculation to complete. Figure 4 is the topology optimization flow chart:

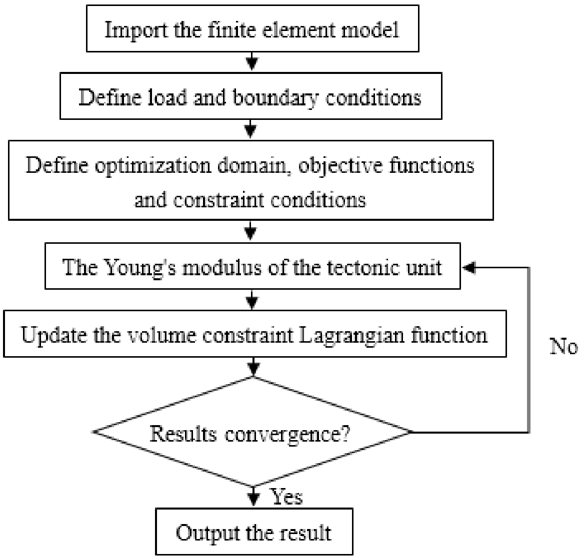


Fig.4 Topology optimization flow chart

4. Simulation analysis

4.1 Optimization of Wall Thickness

Because the robotic big arm joint and fore arm joint is connected in series, the equivalent force and equivalent moment at the end of the arm are related to the mass and the length of the arm, so the optimization begin with forearm arm, and then the big arm.

4.1.1 Optimization analysis of fore arm wall thickness

When the fore arm is optimized, the equivalent force and equivalent moment at the end of the arm is affected by the end load and the arm structure parameters, and load have been confirmed, so analyze the relationship between the total deformation of the end of the arm and the change in wall thickness only, the results of the analysis is shown in figure 5.

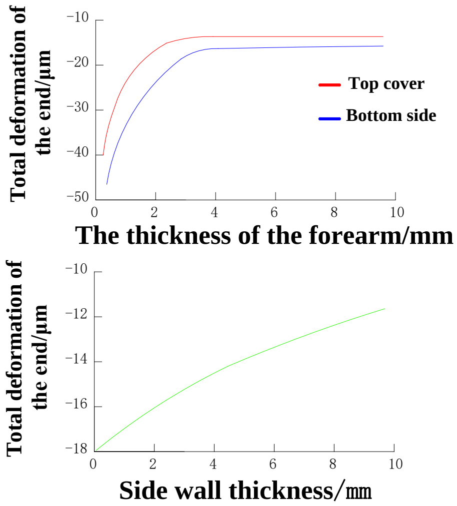


Fig.5 The deformation and the wall thickness

From the results of Fig. 5, it can be analyzed that: the deformation at the end of the arm becomes larger as the wall thickness of top cover of the arm increases, when the wall thickness of the top cover reaches 3mm deformation converge; as the wall thickness of the side wall increases, the deformation at the end of the arm does not converge; the deformation at the end of the arm becomes larger as the wall thickness of bottom side of the arm increases, when the wall thickness of the bottom side reaches 3.5mm deformation converge. It can be concluded that the wall thickness of top cover can be set to 3mm, bottom side set wall thickness of 3.5 mm, side wall thickness remain unchanged.

4.1.2 Optimization analysis of big arm wall thickness

Based on the optimized forearm to optimize the wall thickness of the big arm. Fig. 6 is a graph showing the relationship between the deformation at the end of the big arm and the thickness of the big arm.

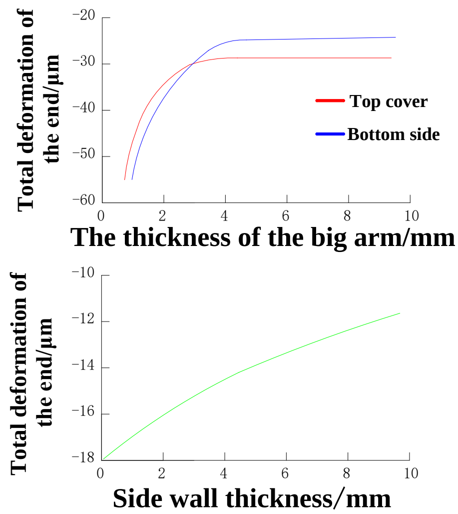


Fig.6 The deformation and the wall thickness

From the results of Fig. 6, it can be analyzed that: the deformation at the end of the arm becomes larger as the wall thickness of top cover of the arm increases, when the wall thickness of the top cover reaches 3.5mm deformation converge; as the wall thickness of the side wall increases, the deformation at the end of the arm does not converge; the deformation at the end of the arm becomes larger as the wall thickness of bottom side of the arm increases, when the wall thickness of the bottom side reaches 4mm deformation converge. It can be concluded that the wall thickness of top cover can be set to 3.5mm, bottom side set wall thickness of 4 mm, side wall thickness remain unchanged.

From the above results, it can be seen that the thickness of the top cover and bottom side are decreased, the thickness of the side wall is constant. Then according to the results to change the arm structure, draw new arm structure model, pave the way for the topology optimization analysis in next step.

4.2 Topology Optimization Method

On the basis of optimization of arm wall thickness above, this paper further optimized. Using the topology optimization method based on the homogenization method to continue to optimize the new arm structure obtained above, decrease the weight of R-θ robot arm, reduce the total flexibility value of the arm, improve the arm and system stiffness, so that the work performance is improved.

4.2.1 Optimization simulation analysis

In this paper, the target optimization function is SCOMP function, the constraint condition is the VOLUME function, the connection area of each joint is set as the non-optimized region, and the other area is set as the optimization area. According to the requirements, the percentage of the volume removal in the optimized area is set to 30%,the optimization algorithm selects the OC method, the convergence error of the iteration results is set to 0.0001, the number of iterative calculation is set to 70 times. After the optimization, the results obtained are indicated in Figure 7-10.

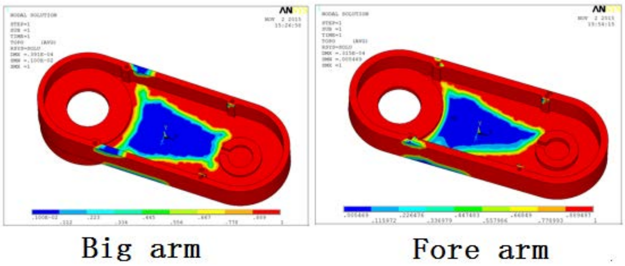


Fig.7 Topology optimization density contours

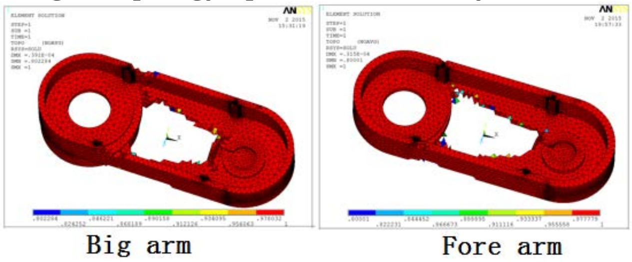


Fig.8 The topology of pseudo density between 0.8 to 1

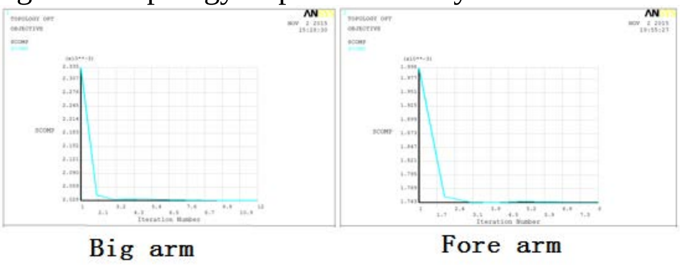


Fig.9 Objective function varies with the number of iterations

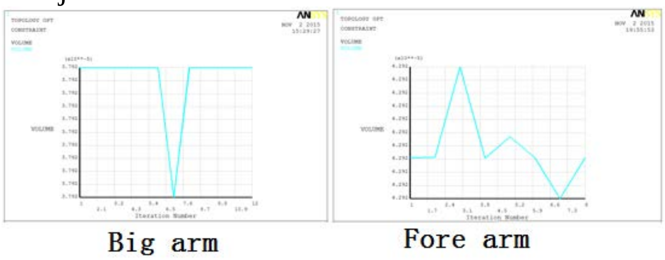


Fig.10 Constrained function change curve

Through topology analysis results can be obtained: the big arm after 12 times of iterations calculation, the minimum total flexibility value of the structure becomes 0.203 × 10-2, 13.2% less than the original; the fore arm after 8 times of iterations calculation, the minimum total flexibility value of the structure becomes 0.175 × 10-2, 12.8% less than the original. After optimized topology analysis, the arm weight decreased, stiffness increased.

4.2.2 Optimized model

In the topology optimization analysis, can according to pseudo density contours of the results to determine removal area of the material, the red area on the pseudo-density contours for the removal zone, the blue area is a reserved area, the area between the two colors for the reduced thickness region. According to the topology optimization results, Figure 11 is the reconstructed three-dimensional model of the arm structure.

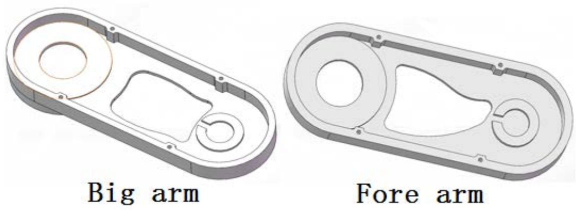


Fig.11 The optimized structure

4.2.3 Comparison of results before and after optimization

Through the finite element modal analyses about the structure of the arm, can understand each order modal characteristics of the structure, avoid the design defects, make the structure more rational, shorten the design cycle and avoid resonance. In this paper, the arm and the system before and after optimization carry on the modal analysis, get the first and second order natural frequency of R-θ robot system. In the analysis of natural frequency and vibration mode, this paper selects the block Lanczons method for analysis, comparative analysis of the results before and after optimization are shown in Table 1.

Table 1 Results compared before and after optimization

Parameter	Before	After	Rangeability
Fore arm weight /kg	1.024	0.834	-18.6%
Big arm weight /kg	1.275	1.096	-14.0%
First order natural frequency /Hz	167.21	189.52	+13.3%
Second order natural frequency /Hz	196.76	207.06	+5.2%

5. Conclusion

1）Set up two kinds of mathematical model of the arm:①Establish the model by taking the arm wall thickness as the influencing factor and the total deformation at the end of the arm as the constraint condition, analyze the influence of wall thickness on the total deformation of the arm;② Establish the arm mathematical model by taking the material removal rate as the constraint boundary and improve the arm stiffness as the goal.

2）Combined with the two optimization methods, can effectively reduce the arm weight and improve the natural frequency of the system: fore arm weight loss of 18.6%,big arm weight loss of 14%, the increase rate of first-order and second-order natural frequency of the system is 13.3% and 5.2%, respectively.

3）The arm optimization method provided in this paper can be extended to other mechanical structure optimization, there is a good applicability.

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