Static optimization design of a printer heat-roller based on sensitivity analysis

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Abstract. Taking the printer heat-roller as the research object, the static characteristics and sensitivity were analyzed by finite element method. Through static analysis, the static characteristics of the heat-roller under working load were obtained, and the size parameters which have great influence on the static characteristics of the structure were determined by sensitivity analysis. The heat-roller was optimized to reduce the self-weight of the structure. It is concluded that the maximum working stress of heat-roller under working load is less than the allowable stress of material, and the structural dimension meets the strength requirement. According to the sensitivity analysis results, it can be seen that the structural parameters which have great influence on the static characteristics of the heat-roller are $d_3$, $d_1$, $l_1$, $l_2$ and $F$. Through optimum design, the weight of the roller was reduced by 15.18%. The analysis results provide a reference for the design of other similar structures.

1. Introduction
The laser printer is commonly used office supply. As one of the key parts of fuser mechanism, the heat-roller is used to pressurize and heat the ink image adsorbed on paper, melt the ink and immerse it in the printing paper to form a fixed image. When the printer works, the heat-roller will rotate periodically at a certain speed, and keep in touch with the pressure roller and paper at the same time. From the structural point of view, the heat-roller belongs to hollow shaft parts. For this kind of shaft parts, fatigue and wear often occur in use, which affects the performance of its use, and will cause parts to break seriously, resulting in serious consequences. There are many reasons for fatigue wear of parts, and load is one of the important factors[1]. In order to understand the impact of load on the damage mechanism of shaft parts, relevant researchers have done some fruitful work. Yang Yang et al. [2] found that with the increase of stress amplitude, the fretting fatigue life of axle steel 35CrMoA will decrease by a smaller margin. The influence of interference fit contact stress level on fretting fatigue life of axle steel LZ50 under rotating bending was studied through experiments by SONG Chuan et al[3]. The results show that the fretting fatigue life of axle steel under rotating bending decreases first and then increases with the increase of interference. Fatigue wear damage of structures is a very complex scientific problem, and the study of static characteristics is the basis of understanding the damage mechanism. For the static characteristics analysis of shaft parts, domestic and foreign researchers have done a lot of useful work. In the literature [4], the static sensitivity analysis of the rotating shaft of a test machine was carried out by combining the orthogonal design experiment method with the finite element software. In the literature [5], the static characteristics of a transmission shaft were studied by three-dimensional modeling and finite element analysis, and the displacement and stress nephograms of the structure were obtained. In the literature [6], on the basis of static
characteristic analysis, sensitivity analysis and optimum design of a transmission shaft were carried out, and the optimum design size of the transmission shaft was obtained. In the literature [7], the static characteristics of a hollow transmission shaft were analyzed by finite element software, and the influence of structural parameters on its static characteristics was investigated. In the literature [8], the static analysis of the gear shaft of helical drill rig was carried out by using finite element method, and the stress, strain, displacement and deformation diagrams of the structure were obtained. In this paper, the stress distribution of a laser printer heat-roller under design load was studied by finite element method, and sensitivity analysis was carried out by means of probability design method. Then the heat-roller was optimized with some key parameters as design variables. The analysis results provide a theoretical foundation for the study of fatigue wear mechanism of the heat-roller.

2. Static analysis of heat-roller based on finite element method

2.1 Finite element model of heat-roller

The schematic diagram of the structure of the heat-roller is shown in Fig. 1. The whole structure of the heat-roller is a hollow shaft. It is made of seamless aluminium alloy tube. The thickness of the tube wall is between 1 mm and 3 mm. The surface is coated with PTFE to prevent the melted toner from sticking to the roller during fixing. As shown in Fig. 1, shaft segment 1 is the spring support part, the bus of the rotary body is a straight line, and shaft segment 2 is the paper contact part, the bus of the rotary body in this section is a spline curve. The material is aluminium alloy. Its material characteristic parameters are as follows: the density is 2700 kg/m$^3$, the Poisson's ratio is 0.3, the elastic modulus is 0.7 e$^5$ MPa, the material yield limit is 70 MPa. In order to meet the reliability of use and make the design safe, a certain safety factor of 1.34 was selected in strength checking, so the allowable stress of material is 52 MPa.

![Fig. 1 Sketch of heat-roller](image)

Before the static analysis, the finite element model was established in the finite element software ANSYS. In order to improve the calculation efficiency, the structure of the heat-roll was simplified to a certain extent on the premise of ensuring the calculation accuracy. The specific simplification principles are as follows: the chamfer structure in the actual structure was not considered. In the process of modeling, firstly, the axial section was established in ANSYS, and then the solid structure of the heat-roll was established by rotation. The whole axis was simulated by solid element solid187. After the solid model was established, the grid was divided. Because the structure is irregular, the free mesh method was adopted, the finite element model of the heat-roller is given in figure 2. The whole model was discretized into 4071 units and 7937 nodes.
After the finite element model was established, it was loaded and restrained according to the actual working conditions of the heat-roller. The specific restraints and loads are as follows: the supporting parts at the left and right ends have radial and axial restraints on the roller, the paper contact parts in the middle of the roller have vertical contact loads. In the analysis, the constraint of spring support was simulated by imposing full restraint on the lower surface nodes of the supporting part, and the effect of contact load was simulated by applying vertical uniform load on the corresponding nodes of the paper contact part.

Through analysis, it can be concluded that the contact load on the paper contact part is mainly caused by the spring support at both ends of the roller. Therefore, the contact load can be calculated by calculating the restraint force of the spring support. After calculation, the contact load is 88.93 N.

2.2 Static analysis results of heat-roller

After analysis, the equivalent force of the heat-roller was extracted according to the fourth strength theory. The stress nephogram of the heat-roller under the action of working load is shown in Fig. 3. It can be seen from the nephogram that the maximum working stress of the heat-roller occurs in the spring support part. The analysis result of extracting stress shows that the equivalent stress of this position is about 7.877 MPa, which is far less than the allowable stress of the material. Therefore, the static strength meets the application requirements.
3. Sensitivity analysis of heat-roller

There are many dimension parameters of the heat-roller. If all parameters are taken into account in the design of the heat-roller structure, the design efficiency will be reduced. Sensitivity analysis can solve this problem well. Sensitivity analysis of the heat-roller is mainly to study the sensitivity of the change of dimension parameters or design variables of the heat-roller to its mechanical characteristics.

In this paper, the influence of the dimension and the material characteristic parameters of the structure on its static characteristics was investigated, and the maximum working stress of the structure was chosen as the objective parameter. Assuming that the parameters are random variables subject to Gauss or truncated Gauss distribution, the probabilistic reliability analysis of the structure was carried out. The dimension and material characteristic parameters of the heat-roller are as follows: length of support position of spring at both ends \( l_1 \), the diameter \( d_1 \), the intermediate length \( l_2 \), slope \( 1/x \) at both ends of the spline curve, inner diameter \( d_3 \), material density \( \text{den} \), Poisson's ratio \( \text{pox} \), elastic modulus \( \text{ex} \), and contact load \( F \). Assuming that the mean value of the variable \( X_i \) is \( X_i \), the variance is 0.1 \( X_i \). In the above variables, considering the relative relationship between the diameter \( d_1 \) at both ends, the minimum diameter \( d_2 \) in the middle and the inner diameter \( d_3 \) of the heat-roller, the constraints are defined: \( d_1 \) is greater than or equal to \( d_2 + 0.1 \), \( d_3 \) is less than or equal to \( d_2 - 3 \). The analysis process was carried out in the PDS module of the finite element ANSYS software. The super-latin sampling method of Monte Carlo method was used to simulate the sampling. The target parameter obtained after 1000 sampling times has converged. The calculation shows that the probability of the maximum working stress not exceeding 16 MPa is 99.7% at 95% confidence level, that is, the static reliability is 99.7%. At the same time, from the analysis results, it can be concluded that the influence degree of the dimensions and material characteristic parameters on the maximum working stress of the heat-roller, that is, the static sensitivity of the roller (as shown in Fig. 4).

Fig. 4 static sensitivity analysis results of heat-roller

From Fig. 4, it can be seen that the design parameters which have great influence on the static characteristics of the heat-roller are \( d_3 \), \( d_1 \), \( l_1 \), \( l_2 \) and \( F \). Among them, \( d_3 \), \( l_2 \) and \( F \) are positively correlated with the target parameters, i.e. the maximum working stress of the structure, while \( d_1 \) and \( l_1 \) are negatively correlated with it.

4. Optimization design of heat-roller

According to the above sensitivity analysis results, the parameters which have greater influence on the static characteristics of the heat-roller were selected as the optimization design variables. Considering that the parameter \( d_1 \) in the actual structure is related to the dimension parameters of other parts, it can not be used as the design variables in optimization. Therefore, the final optimal design variables are \( d_3 \), \( l_1 \) and \( l_2 \), which were used as design variables to optimize the design of the heat-roller on the premise...
that the maximum stress under the working load does not exceed the allowable strength of the material. The mathematical model of optimal design is as follows:

Objective function: \( \text{min } W \); \( W \) — self-weight of heat-roller structure.

Design variables: \( X=(x_1, x_2, x_3)=(d_3, l_1, l_2) \)

Constraints: \( \sigma_{\text{max}} < \sigma \); \( 0.75* d_3 \leq x_1 \leq d_2 - 3 \); \( 0.75* l_1 \leq x_2 \leq 1.25* l_1 \); \( 0.75* l_2 \leq x_3 \leq 1.25* l_2 \)

The sub-problem method in finite element software was used in the optimization process. This method is helpful for fast search and approximation of the optimal value, and the optimization efficiency is high. Through calculation, after 12 cycles, the optimized parameters are rounded to get the optimal parameters of the structure. The values before and after optimization are shown in Table 1. Through optimization, the weight of the structure was reduced by 15.18%.

| parameters   | \( d_3 / \text{mm} \) | \( l_1 / \text{mm} \) | \( l_2 / \text{mm} \) | \( w / \text{kg} \) |
|--------------|----------------------|----------------------|----------------------|-------------------|
| before opt.  | 14.9                 | 20.9                 | 216                  | 0.10391           |
| after opt.   | 17                   | 16                   | 270                  | 0.0881328         |

The static characteristics of the optimized model were analyzed, and the working stress nephogram of the optimized structure was obtained (as shown in Fig. 5). From Fig. 5, it can be seen that the maximum working stress of the structure is 22.7922 MPa, which is still less than the allowable stress of the material. However, compared with the pre-optimization, the maximum working stress of the whole structure is increased, which shows that the use of the material can be achieved by optimizing the design. The efficiency has been further improved and the production cost has been further controlled.

5. Conclusion
In this paper, the heat-roller of a printer was taken as an example, the static characteristics were analyzed. On this basis, the sensitivity analysis and optimization of the structural parameters of the heat-roller were carried out. Through the analysis, the following conclusions are drawn:

(1) Under the working load, the maximum working stress of the heat-roller is 7.877 MPa, and the maximum stress occurs in the spring support part, which is less than the allowable stress of the material, and the static strength meets the application requirements.

(2) The dimension and the material characteristic parameters which have great influence on the static characteristics of the heat-roller structure are \( d_3, d_1, l_1, l_2 \) and \( F \). The maximum working stress of the structure increases with the increase of parameters \( d_3, l_2 \) and \( F \), and decreases with the increase of \( d_1 \) and \( l_1 \).
(3) Through structural optimization design, the weight of the optimized heat-roller structure is reduced by 15.18%.

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