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ANSYS optimization design of lifting mechanism of the vacuum arc furnace

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Abstract: A mechanical model was developed for the lifting mechanism of a prototype of the VCF - 3t cantilevered vacuum arc furnace, the position and value of maximum stress of the column was obtained through force analysis of the main bearing parts (such as column). Then the actual equipment model was simplified to establish finite element model and the stress cloud chart was compared with actual calculated value in order to test the correctness of the finite element model. On this base, combined with the relationships among actual structure sizes of the furnace, the parametric finite element model was established. If the model meet conditions of intensity and stiffness etc., the radius and thickness of the column and furnace body was optimized with the optimizer of ANSYS to make the mass of mechanical structure to be the lightest and make full use of the material' s property. At the same time, VB language was used in the call analysis interface in ANSYS to provide an intuitive man - machine system in order to decrease duplication of workload in series design of product. The parameter optimization method used in this paper is an important development of structural optimization design method and has important practical value in the structural design.
Key words: vacuum arc furnace; finite element analysis; optimization design; lifting mechanism
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In order to improve the design efficiency of product and shorten design period to meet the fast changing demand of markets, parametric model of the vacuum consumable electrode arc furnace ("arc furnace" for short) was established with the finite element analysis software ANSYS. Some mechanical parameters such as intensity, stiffness etc., has been calculated and analyzed. On the basis of meeting the stress criterion, strength analysis and optimization design was carried out emphatically to ensure reasonable load for the whole machine and decrease the mass of furnace to a maximum extent. At the same time, application program with intuitive interface which is convenient for engineering design has been compiled. The program can build model, calculate and analyze automatically after inputting necessary parameters.

The arc furnace can divide into two structure types according to the volume: cantilever type (also called P type, mainly used for the volume under 3t), frame - type (also called H type, mainly used for the volume over 3t). This paper selects the lifting mechanism of 3t P type furnace as design example and the general structure of furnace is shown in Fig. 1. The connector of upright guidance is the part to lift and guide furnace body. As shown in Fig. 2. It' s composed of upright guidance, vacuum transition chamber, intermediate connector, upper connector, hydraulic united. The vacuum transition chamber is a cylindrical annular space welded by double - deck cylinder and flange and connected to furnace body by the lateral flange. It' s the transition passage of gas as evacuation and the gas discharges from the perforated flange with elastic sealing device at the bottom after entering in the interlayer space. The sliding sleeve of inner cylinder cooperates with column to guide the furnace body going up and down. The base of upright guidance was connected to the foundation firmly and the upper end of column and hydraulic cylinder were butted to support the lift

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and rotation of furnace body.

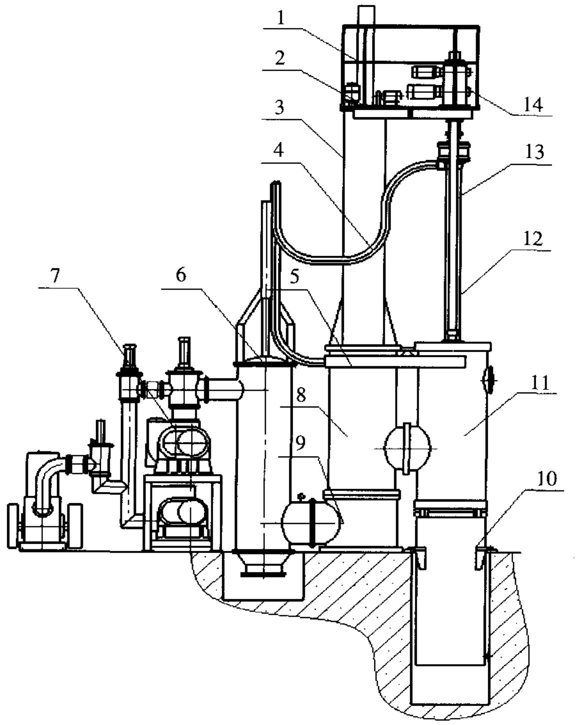

Fig. 1 Overall structure of the arc furnace

1—hydraulic cylinder; 2—hydraulic station; 3—upper connector; 4—water cooling cable; 5—copper bar; 6—deduster; 7—vacuum system; 8—intermediate connector; 9—post; 10—crucible; 11—furnace body; 12—guided post; 13—electrode rod; 14—servo moter

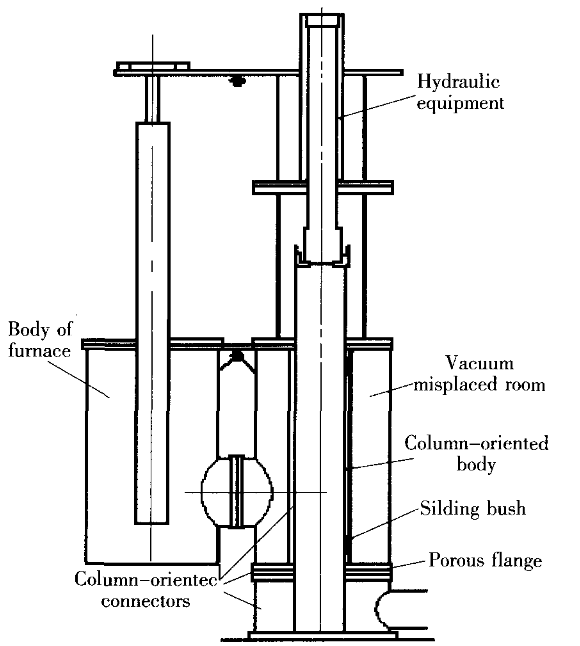

Fig. 2 Connector of the upright post guidance

Steps to establish a parametric model of the arc furnace are: 1) Simplify the force model. Some structures were simplified according to actual situation to conclude the force and constraining conditions; 2) Establish the simplified solid model. Mesh generation was performed in the model and the finite element model with element and node was generated; 3) Set up the type of load and solution analysis option and impose the concluded force and constraining conditions on the finite element model; 4) Observe the solved result through general postprocess to judge if it accord with the required strength; 5) Optimize the designed model. Firstly extract geometric parameters to create the analysis file which composes of pretreatment, solution and post - processing module and extracted optimization variables. Then create optimization control file to control the model according to the extracted optimization variables to make the model has lightest mass on the premise of meeting mechanics requirements.

1 Original model analysis of lifting mechanism

All the main components should be included in the established three - dimensional finite element model such as large column, vacuum transition chamber, connector of the upright guidance, hydraulic lifting equivalent mechanism, platform, servo drive system, electrode system, furnace body, flange and pillar etc. Some basic assumption and simplification has been made as follows according to the structural characteristics and working conditions of vacuum arc furnace:

(1) During working process of vacuum arc furnace the steel structure works in elastic range and there is linear relationship between force and deformation;

(2) The axial deformation of rod is uniformity in the linear elastic range;

(3) The piston and cylinder in hydraulic transmission system is simplified to a pair of pressure in the same size and opposite directions;

(4) Gravity of the electrode system is directly loaded on the platform considering total mass of every component.

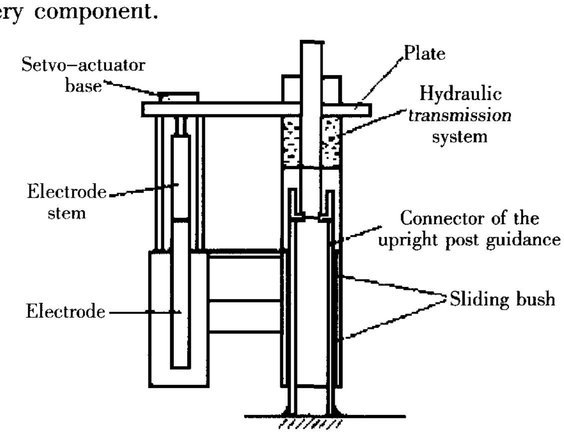

Fig. 3 Schematic of lifting system for electric arc furnace

Schematic of the lifting mechanism for vacuum arc furnace was shown in Fig. 3. It's mainly composed of vacuum transition chamber, connector of

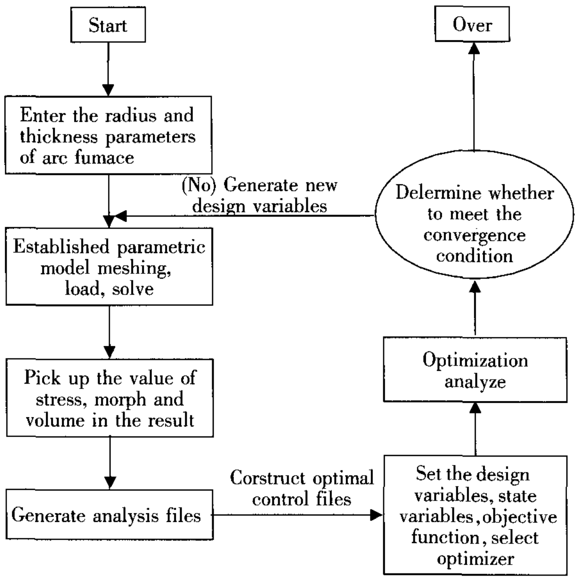

Fig. 4 Optimization flowchart for the arc furnace

the upright guidance, hydraulic transmission system, platform, servo drive system, electrode system, furnace body, etc. Optimization design and analysis was carried out with some relevant physical properties of materials such as mass, stiffness, intensity, etc. Evaluate design schemes to find out the optimal one to improve the structural characteristics and provide reference for further improvement of design size and mass[1]. The schematic of optimization process for vacuum arc furnace was shown in Fig. 4.

2 Structural optimization design of the vacuum arc furnace

2.1 Modeling

Before the parameterized finite element model was established, we should be familiar with its structural characteristics to select the design parameters reasonably[2]. The parameterized modeling flowchart for the vacuum arc furnace was shown in Fig. 5.

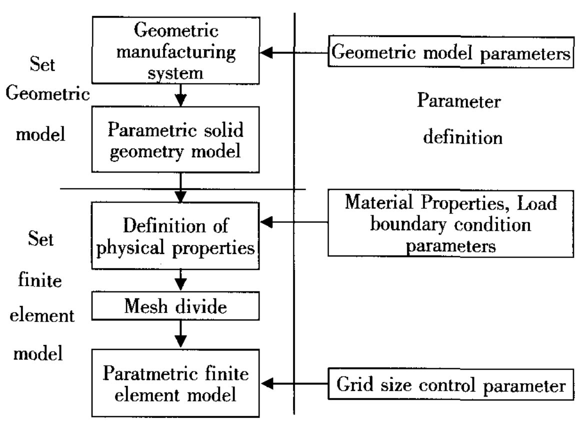

Fig. 5 Parameterized modeling flowchart for the arc furnace

2.2 Extraction of parameterized data

All the parameters selected in parametric finite element analysis were stored in the form of parameter definition module file with APDL. The parameter definition module is the base of parametric finite element modeling analysis and parameters defined by it can also be used by other function module. Then extract parameters of size.

(1) Radius of electrode and crucible

Consumable electrode used in vacuum arc remelting is mainly founded or press formed. To obtain spindles with little segregation of chemical constituent, high density and good surface, the section size of electrode should be larger. At the same time in order to facilitate outgassing and safe operation, the section size should be smaller. So comprehensively considering these two factors the radius of electrode are usually chosen according to the formula as follows in the practical production[3].

$$\left.\begin{aligned} &R_d/R_g = 0.65 \sim 0.85 \\ &\text{or} \quad R_d = \frac{3}{4}R_g \end{aligned}\right\} \tag{1}$$

R_d—radius of consumable electrode; R_g—radius of spindle after crystallization (inner radius of crucible)

In addition, the radius of electrode can also be determined according to the formula as follows by experience.

$$R_d = R_g - \delta \tag{2}$$

δ is the distance between electrode and the wall of water - cooling mould. It should be noticed that δ is must larger than the length of arc during normal remelting to avoid generation of edge arc.

(2) Furnace body

Firstly, the furnace body should have enough space to hold the electrode to meet the requirement of melting process route; Secondly, it's connected to the vacuum system and it can be the buffer for vacuum system as suddenly outgassing at last. It's usually estimated according to the formula as follows[4]:

$$R_L = 2\ R_g \tag{3}$$

The height of furnace body is mainly determined by the difference of maximum length of consumable electrode and length of spindle: $L_L = L_d - L_g$

Where, L_L—length of furnace body; L_d—length of electrode; L_g—length of spindle.

(3) Length of electrode and crucible

The mass of consumable electrode is equal to that of spindle so the length of electrode can be calculated as follows:

$$L_d = 4\ m/(\pi\rho_d \cdot R_d^2) \tag{4}$$

And the length of spindle:

$$L_D = 4\ m/(\pi\rho_g \cdot R_g^2) \tag{5}$$

The crucible is impossible to be filled with liquid steel so the length of crucible should be longer than that of spindle about 350 mm in the design.

$$L_D = L_D + 350 \tag{6}$$

The content of parameterized definition module file was classified and listed in Table 1.

Table 1 The parameter classification table of the model

Type	Value			
Geometric model	m = 3000 kg $A = 1$	$H = 2\ 000$ mm $R_L = 2R_g$	$R_d = 190$ mm $B_L = 10$ mm	$R_g = 221.5$ mm $L = 550$ mm
Parameters	$R_z = 180$ mm $L_g = 4\ m/(\pi \cdot \rho_g \cdot R_g^2) + 350$	$L_L = L_d - L_g$ $L_d = 4\ m/(\pi \cdot \rho_d \cdot R_d^2)$	$B_z = 30$ mm	$\pi = 3.14$
Material characteristic	$B_1 = 210\ 000$ mm	$B_2 = 0.3$ mm	$\rho_g = 8\ 200$ kg/m^3	
Parameters	$\rho_D = 7.85 \times 10^{-6}$ kg/m^3	$\rho_d = A \cdot \rho_D$	$\rho_l = 7.85 \times 10^{-6}$ kg/m^3	

Finite element model parameters of the furnace structure were presented as follows:

(1) Geometric model parameters

Geometric model parameters mainly refer to the structural size parameters. Not all the size parameters in the finite element analysis model need to be parameterized. Because the geometric model reflects the physical characteristics of structure actually it should be convenient to calculation and analysis. The numbers of geometric model parameters involved in this paper are totally 14, in which there are 10 parameters changing independently (i. e. main parameters). And other 4 parameters which can't change independently including D_L, L_D, L_d, L_L are constrained by main parameters and determined by one main parameter at least.

(2) Material characteristics and constant parameters

The material used in vacuum arc furnace is almost Q235. Some dangerous place should be reinforced with stiffener. Material characteristic parameters mainly include Young modulus, Poisson ratio, density, etc. Usually the value of Poisson ratio is in the range of 0.25 ~ 0.3 and that of Young modulus and density are related to materials. However, the density of electrode and spindle vary with the kind of metal (such as Ti, steel) so it was treated as parameter and inputted later.

(3) Loading parameters

Some loading parameters vary with the structure such as dead weight. The software can calculate the volume after inputting demand and then according to the density of materials it can be calculated automatically. It has been presented that the electrode doesn't have entity structure but is added in the form of mass so the loading must be treated as parameter.

2.3 Variable selection in structural optimization of vacuum arc furnace

(1) Selection of objective function

The overall structure of vacuum arc furnace is safe but its deadweight is very large and the stress is uneven. Weight was selected as an objective function to design more reasonable structures.

(2) Selection of design variables

In order to reduce quality and at the same time ensure the whole performance of the furnace meeting the operating requirements, the furnace body, thickness of column and radius, etc. were selected as design variables through analyzing the effect of each component on overall structure.

(3) Determination of state variables

The allowable stress of furnace and stability allowable stress of column were calculated preliminarily and the design variables were constrained by these results.

The selection of optimization variables and its allowable error were shown in Table 2.

Table 2 The list of optimization variables

Optimization variables	Appellation & alphabetic symbol	Minimum	Maximum	Admissible error
Objective function	Weight wt/kg	As light as possible	—	2
Design variables	Columniation radius R_z/mm	152	200	0.1
	Columniation thickness B_z/mm	10	30	0.01
	Body radius R_L/mm	360	450	0.1
	Body thickness B_L/mm	4	10	0.01
State variables	Steady absolute admissible stress seqv_1/MPa	0	56.4	0.01
	Absolute admissible stress seqv_2/MPa	0	117.5	0.01

3 Result analysis

The design variables are R_z, R_L, B_z, B_L. State variables are stress and stability stress and the objective function is to have lightest mass. The optimization result is shown in Table 3.

Table 3 Comparison of design variables before and after optimization

Optimization variables	Original value	Optimized value	Round value
R_z/mm	180	161.14	161
B_z/mm	30	10.041	10
R_L/mm	443	360.22	360
B_L/mm	10	4.0124	4

As shown in Fig. 6, there are totally 35 iterative steps in optimization process and the 21st step is the optimal value.

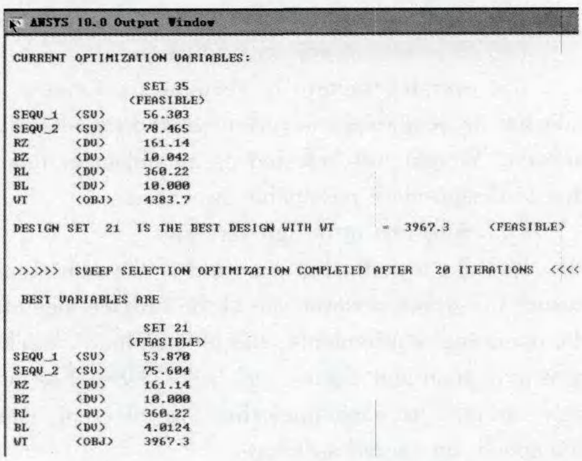

Fig. 6 The result of optimum design

The optimal value of objective function WT was shown in Fig. 6. The mass decreases from 5 874 kg to 3 967.3 kg and the optimized mass is 67.5% of the original one. The schematics of calculated model and result were shown in Fig. 7 and Fig. 8.

From Fig. 7 and Fig. 8 we know that the maximum value of overall stress is53.233 MPa and it's smaller than the allowable stress which is 117.5 MPa. The maximum deformation of the overall furnace structure is at the top and its value is 14.699 mm. The maximum height from ground after the furnace lifted is 9 850 mm and the deflection is 0.0015.

4 Conclusion

According to the series characteristic of the vacuum arc furnace structure, a parameterized finite element analysis model combines VB and ANSYS has been developed with the second developing tool of ANSYS. And on this base, the overall structure has been optimized by optimization design method which can ensure the model meeting the demand of static deformation and strength.

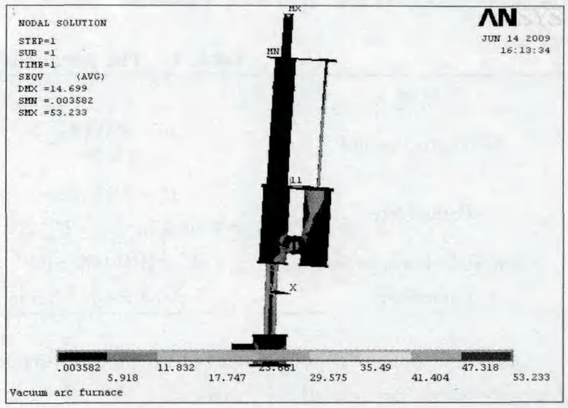

Fig. 7 The VM stress nephogram of the arc furnace

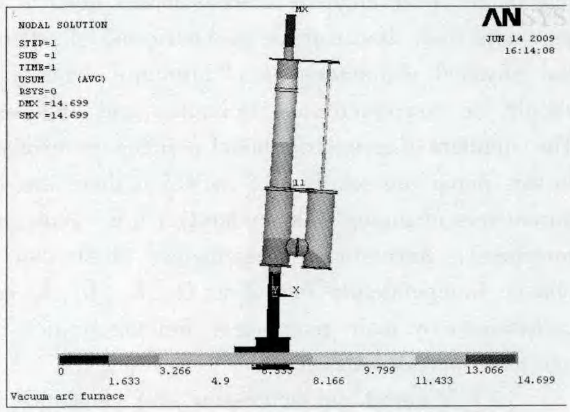

Fig. 8 The displacement nephogram of the arc furnace

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