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Optimal disc cutters plane layout design of the full-face rock tunnel boring machine (tbm) based on a multi-objective genetic algorithm †

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Abstract

Improving of the quality of the disc cutters' plane layout design of the full-face rock tunnel boring machine (TBM) is the most effective way to improve the global performance of a TBM. The plane layout design of disc cutters contains multiple complex engineering technical requirements and belongs to a multi-objective optimization problem with multiple nonlinear constraints. Based on analysis of the technical requirements of the plane layout problem, an optimizing mathematical model was built. To obtain a set of design schemes for engineers to choose from, a multi-objective genetic algorithm (MOGA) was applied to carry out the optimization of the mathematical model. A constraint-domination principle was utilized to handle the constraints, and a nondominated sorting method was adopted to obtain Pareto solutions. Simulation results showed that the proposed method was efficient and accurate in obtaining the Pareto layout solutions.

Keywords: Disc cutters plane layout; Full-face tunnel boring machine; Multi objective optimization; Nondominated sorting

1. Introduction

With the mushrooming of tunneling projects for underground space, the full face rock tunnel boring machine (TBM) has become more important. Today, the TBM has been widely applied to subways, railways, highways and water-electricity projects, etc. The layout design of disc cutters for the TBM is one of the key issues and contains key technologies in the TBM design [1]. It directly affects the boring performance, the service life, the main bearing of the cutter head, and the degree of vibration and noise of the TBM.

In designing the layout of the disc cutters on the cutter head, a key issue is to study the process of the cutters' penetration into rock and build a practical cutting force model. Researchers have studied and built various cutting force models that can be used to calculate the normal force and the rolling force. These models can be divided into semi-theoretical models and empirical models. The semi-theoretical models are built based on the linear cutting machine (LCM) testing and the theoretical analysis, e.g., the Colorado School of Mines (CSM) model [1, 2]. The empirical models are built based on the historical field performance of the TBM, e.g., the Norwegian Institute of Technology (NTH) model [3]. Among all the cutting force models, those that consider the effects of ground conditions, the rock properties, the machine parameters, and the operational and practical constraints are widely accepted and applied in engineering practice (e.g., the CSM and the NTH).

The disc cutters layout design correlates with the disc cutters' head force, the crushed rock's mobility and the manufactural process of the cutter head. Improving the quality of the disc cutter's layout scheme is the most effective way to improve the boring performance of the TBM [4]. Layout design of the disc cutters includes the spacing design and the plane (circumferential) layout of the disc cutters. In studying the spacing design of the disc cutters, many researchers adopted the numerical simulation method [5-7] and the linear cutting machine (LCM) experimental method [1, 4, 8-10]. After the spacing of the disc cutters is determined, the next step is to carry out the plane layout of the disc cutters on the cutter head. The CSM model can be used to perform this step. Rostami [11] studied the methods of the hard rock TBM cutter head modeling. The model they built was based on the estimation of the cutting forces and it proved to be a successful tool for cutter head design optimization as well as for performance estimation. Zhang [12] studied the spiral layout rule of the disc

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cutters and presented a simplified equation of the cutting force distribution on the cutter head.

This study focused on the second step of the disc cutters' layout design, which is the plane layout design. The plane layout design should meet multiple constraints including geometry constraints and other performance constraints. It belongs to a multi-objective engineering optimization design problem with multiple nonlinear constraints. A practical multi-objective optimization model is needed and advanced computational methods are to be studied for the disc cutters' plane layout.

In this study, a multi-objective optimization model with multiple constraints was built and the corresponding MOGA was applied to obtain a set of Pareto layout schemes for engineers to choose from. An instance of a disc cutters' plane layout design is presented.

2. Problem statements

As shown in Fig. 1, the discs are so arranged that they contact the entire cutting face in concentric tracks when the cutter head turns. The rotating cutter head presses the discs with high pressure against the cutting face. The discs therefore make a slicing movement across the face. When the pressure at the cutting edge of the disc cutter exceeds the compressive strength of the rock, the rock will be crushed. The cutting edge of the disc cutter pushes the rolling into the rock, until the advance force and the anti-crush force of the rock are in balance. Through this displacement, described as a penetration, the cutter disc creates a high stress locally, which leads to long flat pieces of rock (chips) breaking off. According to the relative reference [11, 12] and practical engineers' experiences, technical requirements of disc cutters layout design are summarized as follows:

① The amount of the eccentric forces of the whole system are expected to be as small as possible;

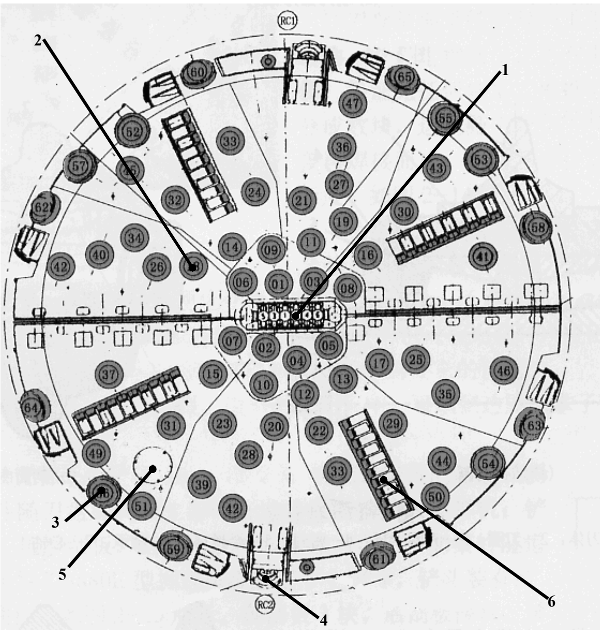
② The amount of the eccentric moments of the whole system are expected to be as small as possible;

③ All the adjacent disc cutters are to crush the rock successively to keep the high cutting efficiency;

④ All the disc cutters are to be contained within the cutter head, with no overlapping among each other;

⑤ The position error of the centroid of the whole system is not to exceed an allowable value, and the smaller the better;

⑥ All the disc cutters should not interfere with manholes or buckets. As shown in Fig. 1, uniform positioning of the muck buckets around the periphery of the cutter head may interfere with the allocation of the cutters. In those cases, positions of the buckets take priority, since the distances among the buckets have to be equal [11].



1-Center cutters; 2-Normal cutters; 3-Gauge cutters; 4-Reaming cutters; 5-manhole; 6- muck buckets

Fig. 1. A disc cutter layout scheme [13].

3. Mathematical model

Suppose that the set of disc cutters to be located on the cutter head is:

$$\text{CUTs}=\{\text{Cut}_1, \text{Cut}_2,\cdots, \text{Cut}_i,\cdots,\text{Cut}_n\}$$

where n is the total number of the disc cutters. In this study, as shown in Fig. 1, all the disc cutters are simplified as circles and regarded as rigid bodies with uniform mass distribution. So the ith cutter is denoted as $Cut_i\,(p_i, r_i)$, where $p_i=(\rho_i,\theta_i,\gamma_i)^T \in R^3$ is the position of a reference point (the centroid of the object in this paper) of the ith cutter in the coordinate system $oxyz$; $\rho_i \in (0,R)$ is the radius of ith cutter measured from the center of the cutter head; $\theta_i \in [0,2\pi)$ is the position angle of the ith cutter; $\gamma_i \in [0,0.5\pi)$ is the tilt angle of the ith cutter, r_i is the radius of the cutter. Generally, the tilt angle of the normal cutter is zero, and the masses and dimensions of all the disc cutters are given in advance, so p_i are variables to be manipulated in the following procedure. Before the disc cutters plane layout design, the radius $\rho_i \in (0,R)$ of the cutters and the tilt angle $\gamma_i \in [0,0.5\pi)$ of the cutters have been determined. Thus, a general disc cutters plane layout scheme of a cutter head can be formulated as:

$$X = \{\theta_1,\theta_2,\cdots,\theta_n\}, i = 1,2,\cdots,n \tag{1}$$

Then based on the technical requirements of disc cutters plane layout design, the mathematical model of the disc cutters plane layout problem can be formulated as follows:

Find a layout scheme $X\in R^{3n}$, such that

$$\min_{X=D} y = f(\boldsymbol{X}) = (f_1(\boldsymbol{X}), f_2(\boldsymbol{X}), f_3(\boldsymbol{X})) \tag{2}$$

s.t.

Overlapping constraints：

$$g_1(\mathrm{X}) = \sum_{i=0}^{n-1} \sum_{j=i+1}^{n} \Delta V_{ij} \le 0 \tag{3}$$

Static balance constraints：

$$\begin{aligned} g_2(\mathrm{X}) &= |x_m - x_e| - \delta x_e \le 0 \\ g_3(\mathrm{X}) &= |y_m - y_e| - \delta y_e \le 0 \end{aligned} \tag{4}$$

Manholes and buckets constraints:

$$g_4(\mathrm{X}) = \{\forall i \in \{1, \cdots, n\} : cut_i \cap OP \in \varnothing\} \tag{5}$$

where D denotes the feasible region of variable X, $\mathrm{f}_1(\mathrm{X})$ denotes the side force F_s of the cutter head. $\mathrm{f}_2(\mathrm{X})$ denotes the eccentric moments of the cutter head. $\mathrm{f}_3(\mathrm{X})$ denotes the unsuccessive cutters' number. In this paper, a semi-empirical cutting force model proposed by Rostami [11] was adopted to calculate the normal force. ΔV_{ij} denotes the overlapping area between the Cut_i and the Cut_j. O_m (x_m, y_m) is the real centroid of the whole system and O_e (x_e, y_{ee}) is the expected position of O_m. $cut_i \cap OP \in \varnothing$ denotes the ith cutter is not overlapped with the manholes and the buckets.

4. A Pareto-based multi-objective genetic algorithm for the disc cutters plane layout design

It can be seen from the mathematical model that the disc cutters plane layout problem belongs to a multi objective optimization problem with multiple performance constraints. To obtain a set of design schemes for engineers to choose from, this work studied a Pareto-based multi-objective genetic algorithm to solve the problem and overcome the defects of the traditional methods. Traditional methods for solving the multi-objective optimization problems (MOPs) are to scalarize the objective vector into a single objective. In those cases the obtained solution is highly sensitive to the weight vector used in the scalarization process and demands the user to have knowledge about the underlying problem. Moreover, in solving multi-objective problems, designers may be interested in a set of solutions instead of a single solution. The ability of the multi-objective optimization algorithm (MOAs) to find multiple solutions at a single run and the fact that it can incorporate any number of objectives makes it well-suited to tackle the problem.

There exist a few studies on the multi-objective algorithms, in which the Pareto algorithms [14-16] use the dominance relations among the individuals. Therefore many researchers study the Pareto algorithms that use the dominance relations among the individuals to evaluate the individuals. The Pareto algorithms include the nondominated sorting genetic algorithm (NSGA) [15] and the NSGA-II [17]. These algorithms fully utilize the multi-objective optimization theory and the advantage of the evolutionary algorithm, and will be a promising way to solve complex multi-objective optimization problems. In this study, a Pareto-based multi-objective genetic algorithm was adopted to solve the disc cutters plane layout problem.

4.1 Constraints handling of the multi-objective problems

The most important works in the study of MOAs is the handling of constraints that directly affects the MOAs' efficiency. Considering the multi-objective optimization problems with constraints, the constraints divide the search space into several feasible spaces and several infeasible spaces; it will increase the complexity of the domination relation among the individuals. Many investigators study the handling of the constraints. Among all the methods, the most commonly used method is the penalty function approach [18-20], where a penalty that is proportional to the total constraint violation is added to all the objective functions. When applying this procedure, all the constraints and objective functions must be normalized, which is difficult for large-scale complex problems. Therefore, Deb [21] defines a constraint-domination principle, which differentiates infeasible from feasible solutions during the nondominated sorting procedure. Vieira [22] proposes a method of treating constraints as objectives in a multi-objective optimization problem, in which all the constraints are transformed into two new objectives: one is based on a penalty function and the other is made equal to the number of the violated constraints. To ensure the convergence to a feasible Pareto optimal front, the constrained individuals are eliminated during the elitist process. Inspired by the above-mentioned ideas, many researchers study the method of transforming constraints into objectives and have achieved good results.

As shown in Eqs. (3)-(5), the disc cutters' plane layout problem contains the overlapping constraints, the static balance constraints and the manholes and buckets constraints. These constraints are very strict and should be first satisfied during the optimization process, so this study adopted the strategy of "constraint-domination first" when comparing the domination relations among the individuals.

4.2 Nondominated comparison among the individuals

A strategy of "constraint-domination first" was adopted in this paper. To denote the constraints violating degree of the solution $\boldsymbol{X}_i$, the constraint violation of a solution $\boldsymbol{X}_i$ can be defined as follows:

$$\varphi(\boldsymbol{X}_i) = \sum_{j=1}^{n} [\lambda_j g_j(\boldsymbol{X}_i)]^2 \tag{6}$$

Where, $\varphi(\boldsymbol{X}_i)$ denotes the distance of the solution $\boldsymbol{X}_i$ to the feasible space. The greater its value is, the farther away it is from the feasible space. If $\varphi(\boldsymbol{X}_i)=0$, then $\boldsymbol{X}_i$ is a feasible solution. In practice, an infeasible threshold φ_c usually is given. If $\varphi(\boldsymbol{X}_i) \le \varphi_c$, then take the solution $\boldsymbol{X}_i$ as a feasible solution. λ_j denotes the weight of the jth constraints. Different constraints have different order of magnitude, so there is a need to set different weights for each constraint to balance all the constraints in the same order of magnitude.

A constraint-domination principle proposed by Deb [18] can be described as follows: A solution $\boldsymbol{X}_i$ is said to constraint-dominate another solution $\boldsymbol{X}_j$, if any of the following conditions is true:

(1) Solution $\boldsymbol{X}_i$ is feasible and solution $\boldsymbol{X}_j$ is not;

(2) Solution $\boldsymbol{X}_i$ and $\boldsymbol{X}_j$ are both infeasible, but solution $\boldsymbol{X}_i$ has a smaller overall constraint violation;

(3) Solution $\boldsymbol{X}_i$ and $\boldsymbol{X}_j$ are feasible and solution $\boldsymbol{X}_i$ dominates solution $\boldsymbol{X}_j$.

4.3 Nondominated sorting among the individuals

The selection operator of the MOGAs differs from that of the simple genetic algorithms. Before the selection is performed, the nondomination sorting method is used to rank the population. In this study, the nondominated sorting mechanism proposed by Srinivas and Deb [14] is adopted to ensure the population converge to the Pareto-optimal front and keep the diversity of the population. All the individuals are decomposed into different fronts according to the nondominated sorting mechanism. Srinivas and Deb adopted an excluding distance method to compare the individuals in the same front to obtain the more uniform distributed Pareto set. For the disc cutters' layout problem, to get a set of Pareto optimal solutions, the differences among the individuals were used as the sub-evaluation criteria. The greater the differences are, the more outstanding the individuals are. The difference of a solution $\boldsymbol{X}_{ki}$ from other solutions in the kth front can be defined as follows: select r solutions randomly from the kth front, calculate the sum of the distance $D(X_{ki})$ between the solution $\boldsymbol{X}_{ki}$ and the r solutions, and take the $D(X_{ki})$ as the difference of the solution $\boldsymbol{X}_{ki}$.

In this study, the sorting rule is as follows: Sort the individuals in the same front by the difference value of each individual, and then assign each individual a fitness value according to the sorting result. Suppose p denotes the sorting position of an individual $\boldsymbol{X}_{ki}$ in the kth front, Nf denotes the number of the fronts, N denotes the population size, N_k denotes the number of individuals in the kth front, then the fitness value of $\boldsymbol{X}_{ki}$ can be formulated as follows:

$$Fitness(X) = \frac{(Nf - k) \times N}{Nf} + Sp \times \frac{(N_k - p)}{N_k} \tag{7}$$

where, Sp denotes the selection pressure. In this study $Sp = 0.5$.

4.4 Procedure of the MOGA

The procedure of the MOGA as shown in Fig. 2 can be described as follows:

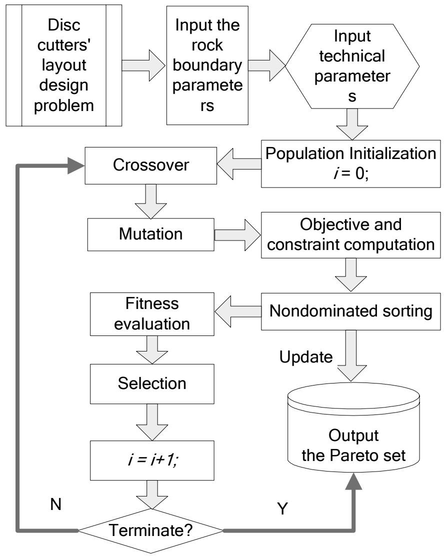


Fig. 2. Flowchart of the MOGA.

Step 1. Input the rock physical properties, the cutter head geometry parameters, the whole technical requirements and the operator parameters of the MOGA, initialize the population, clear the Pareto set, set count i=0;

Step 2. Operate the crossover and mutation operators.

Step 3. Compute the objectives and constraints of all individuals.

Step 4. Combine the current population with the parent population, and sort the combined population by using the nondominated sorting method;

Step 5. Update the Pareto set;

Step 6. Calculate the fitness values of the individuals according to the sorting result;

Step 7. Select the next population based on the fitness value of the individuals；

Step 8. Judge whether the termination criterion is satisfied: if yes, go to Step 9；if not, go to Step 2；

Step 9. Output the Pareto set.

5. Application instance

Taking the disc cutters layout design of a full face rock TBM for a water tunnel project as a background, forty-one disc cutters are to be located on the cutter head surface shown in. Fig. 1. The relative parameters are listed in Table 1. The rock is mainly in granite-based geology. According to the engineering requirements, there are four manholes and eight symmetrically distributed buckets on the cutter head. The locations of the manholes and the buckets are listed in Table 2 and Table 3, respectively. The basic problem is to optimize the objective function formulated by Eq. (2) while satisfying the technical constraints given by Eqs. (3)-(5).

The numerical experiments were run on an AT-compatible PC, Intel processor of 1700MHz and memory of 512M. Parameters set in the FEM calculation are: the calculated FEM platform is ANSYS (R) Release 10.0, unit Shell63 was adopted, the number of units is 63369, the number of nodes is 62193, the density is 7850Kg/m^3, the elastic modulus E=2.06 $\times$ 105MPa, and Poisson's ratio is 0.3.

An MOGA was used to solve the disc cutters plane layout problem. The performance indices of the obtained optimal layout scheme are listed in Table 4. The original disc cutters Layout scheme used in the project is illustrated as Fig. 3. The obtained optimal scheme of this study is illustrated as Fig. 4. The differences of the Pareto solutions are illustrated in Fig. 5. The obtained maximum stresses and deformations of the cutter head under two different loading conditions (the normal loading condition and the full loading condition) are listed in Table 5. For the normal loading condition, forces exerted on the tip of the cutters were calculated by a semi-empirical cutting force model proposed by Rostami [11]. For the full loading condition, forces exerted on the tip of the cutters were determined by the maximum normal force of the cutter. The obtained stress distribution and deformation distribution of the cutter head under two loading conditions are shown in Fig. 8.

Table 1. Parameters setting.

Content		Value
Punch shear strength of rock (MPa)		7~13
Uniaxial compressive strength of rock (MPa)		50~93.6
Brazilian tensile strength (MPa)		2.14~4
Cutter head radius (m)		4.015
Rotational speed of cutter head (rad/s)		0.6283
Mass of each cutter (kg)		200
Diameter of each cutter (mm)		483
Cutter tip width (mm)		10
Cutter penetration (mm)		7
Cutter edge angle (rad)		1.5708
Number of the center cutter		8
Number of the gage cutter		10
Number of the normal cutter		33
Expected centroid position of a cutter head (mm)	x_e	0
	y_e	0
Allowable centroid error of the whole system (mm)	δx_e	5
	δy_e	5
Number of manholes		4
Number of the buckets		8
Radius of the manholes (mm)		200

Table 2. Locations of the manholes.

No.	ρ /mm	θ /rad
1	2700.000	1.2217
2	2700.000	2.793
3	2700.000	4.363
4	2700.000	5.934

Table 3. Dimensions and locations of the buckets.

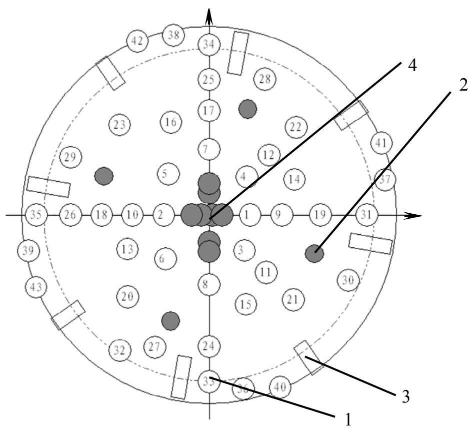
No.	ρ /mm	θ /rad	Length/mm	Width/mm
1	3700.000	0.611	700.000	300.000
2	3500.000	1.396	900.000	300.000
3	3700.000	2.182	700.000	300.000
4	3500.000	2.967	900.000	300.000
5	3700.000	3.753	700.000	300.000
6	3500.000	4.538	900.000	300.000
7	3700.000	5.323	700.000	300.000
8	3500.000	6.109	900.000	300.000

Table 4. Performance indices of the optimal layout scheme and the original scheme.

Indexes	Original layout scheme	The optimal scheme	
		Best	Average
M_v / KN.m	154.840	0.05	4.74
F_s /KN	11.558	0.12	5.35
x_m /mm	-2.135	0.28	-0.13
y_m /mm	-0.221	-0.35	-0.55
Overlapping area	0.000	0.000	0.000
Unsuccessive disc cutters' number	4	0	3
time/S	Unknown	1512	1543

Table 5. The maximum stresses and deformations of the cutter head of the optimal scheme.

Loading conditions			Value
Von Mises Stress/MPa	Normal loading	Max	93.62
		average	41.36
	Full loading	Max	315.23
		average	105.07
Max Deformation/mm	Normal loading	Max	0.40
		average	0.22
	Full loading	Max	1.28
		average	0.71



1 Normal cutters and gage cutters; 2 Manholes; 3 Buckets; 4 Center cutters

Fig. 3. The original disc cutters Layout scheme.

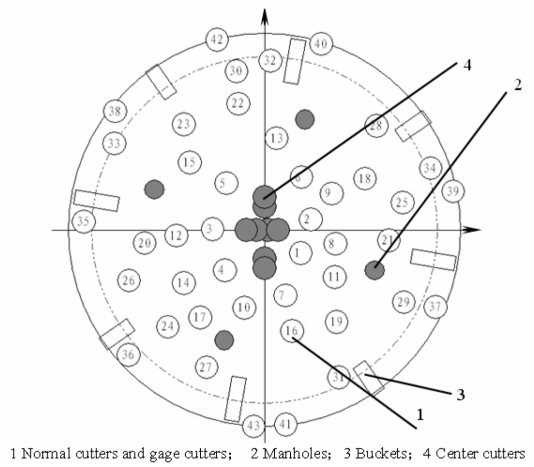


Fig. 4. The optimal disc cutters layout scheme obtained by the proposed method.

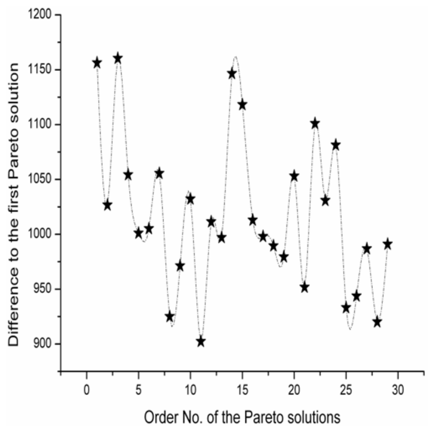


Fig. 5. Pareto solutions differences of the Pareto set obtained by the proposed method.

The geometry parameters of cutter head are shown in. Fig. 7. The unit of the geometry parameters of the cutter head is the millimeter.

The data in Table 4 show that, compared with the original disc cutters layout scheme, the scheme obtained by the MOGA is more superior in that:

① The side force and the eccentric moment of the cutter head of the optimal scheme are smaller than those of the original scheme.

② As shown in Figs. 3 and 4, the optimal scheme can make all the adjacent cutters more successively into rock with a relatively larger position angle difference;

③ The static balance value of the cutter head of the optimal scheme is lower than that of the original disc cutters layout scheme;

④ As shown in Fig. 5 after one running time, MOGA can provide a set of various layout schemes for the engineers to choose from.

For the optimal scheme obtained by the proposed method, data in Table 5 and Fig. 8 show that both the distributions of

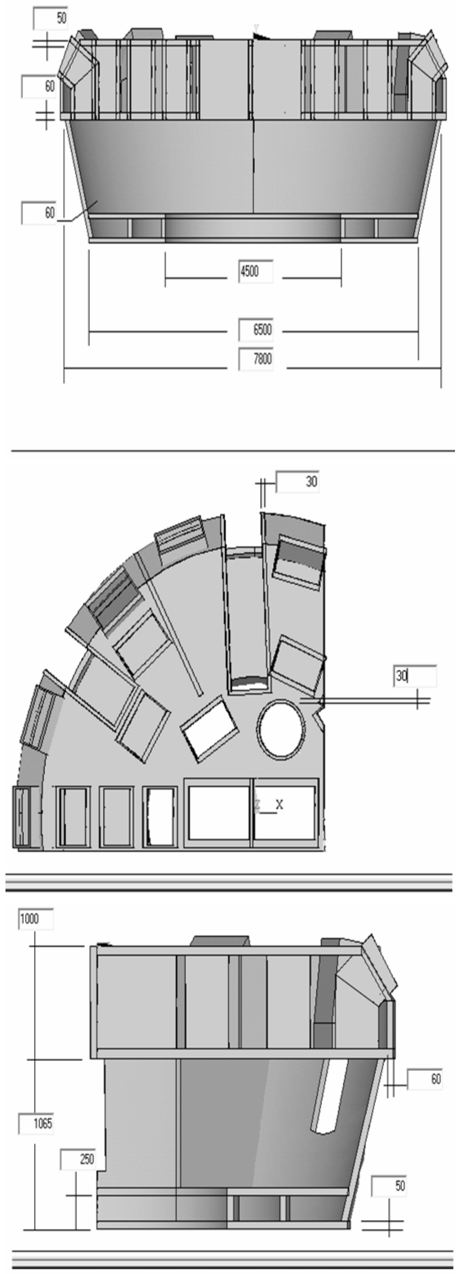
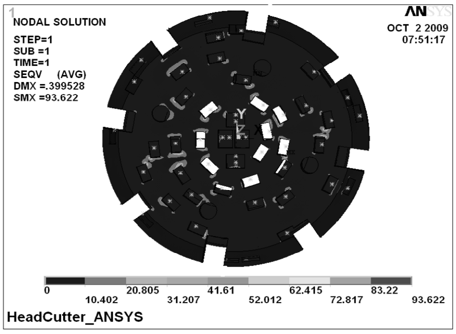


Fig. 6. Geometry parameters of the cutter head.

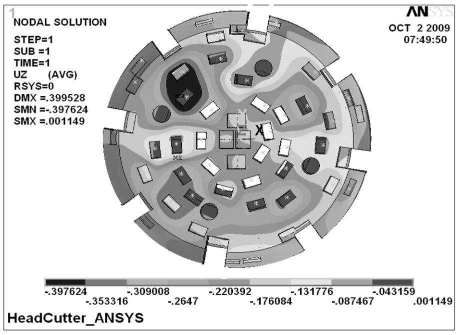
the stress and deformation of the cutter head under the normal and full loading conditions are uniform and meet the technical requirements. The maximum stress values of the normal and full loading conditions are about 93Mpa and 315Mpa, respectively. The maximum deformation values of the normal and full loading conditions are about 0.4mm and 1.28mm, respectively.

6. Conclusions

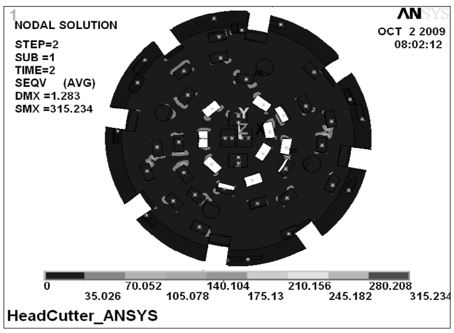
Considering the complex engineering technical requirements, a mathematical model of the plane layout design of the disc cutter was built. To provide a set of disc cutters layout schemes for engineers to choose from, the MOGA was adopted to solve the disc cutters' plane layout problem. The computational results show that by using the mathematical model and the MOGA, a set of Pareto layout schemes with better technical indices than the scheme obtained by the traditional method can be obtained efficiently and accurately.



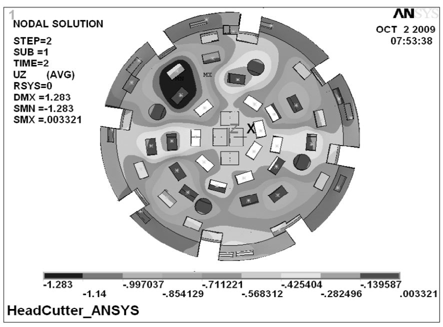
Stree distribution under normal load condition



Deformation distribution under normal load condition



Stree distribution under full load condition



Deformation distribution under full load condition

Fig. 7. Stress and deformation distributions of the cutter head under two loading conditions of the optimal scheme.

Acknowledgments

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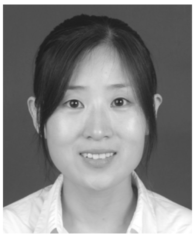

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