Research on Scheduling of Furnace Loading Quality Maximization in Forging Heat Treatment Process

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Abstract. In this paper, the optimal scheduling problem of batch furnace charging is carried out for the furnace of the heat treatment process system in the forging industry. The scheduling research aims at maximizing the quality. Firstly, according to the production capacity of each heating furnace in the system, the maximum capacity and the minimum energy consumption of the system are solved and the loading capacity of each furnace under the optimal production is given. Then through the continuous batching of the forging batch furnace charging, and regress to the discrete problem research. Finally, the optimization research of the furnace quality is realized, which provides a new scheme for the research of the forging furnace charging scheduling problem.

1. Introduction
The energy saving and emission reduction of the forging industry is currently highly valued by industry professionals and related scholars. In the forging industry, research on energy saving and emission reduction has focused on the design and development of advanced forging heating equipment, the application and promotion of new materials, and the improvement and optimization of process procedures. At the same time, some scholars have optimized the solution to the problem of furnace charging scheduling for forgings. For example, Song Jiwei[1] took the problem of roll heat treatment scheduling as the actual background, studied the two-stage and three-stage non-waiting mixed flow shop scheduling problem, and then combined the discrete particle population optimization algorithm to solve the established integer programming model. Jiang Mingming[2] et al. established an energy-saving scheduling model for forging furnace charging with the objective function of the forging billet charging capacity difference rate. The effectiveness and feasibility of the energy saving scheduling model and its solution method for forging billet furnace charging are verified by solving the problem with genetic algorithm. Liu Jianjun[3] et al. proposed a production planning and control method based on load control theory, established a shop load model and gave a heat treatment sequencing decision method considering load dynamic equilibrium.

At present, in the research of forging furnace charging scheduling, the main research contents include the sequential scheduling of forgings furnace charging and the multi-forging blank mixing furnace charging to reduce the furnace charging capacity difference rate et al. But the heating efficiency of the heating furnace is closely related to the quality of the furnace charging. The quality of the furnace charging is positively correlated with the heating time of the furnace.

In this paper, the heat treatment process is firstly modeled and analyzed, and then the maximum furnace loading quality is solved to obtain the maximum production capacity and minimum energy consumption of the system, so as to maximize the quality of forging furnace loading and improve the utilization rate of heating furnace.
2. Analysis of System Loading Problems in Heat Treatment Process

As the core process link of the forging industry, heat treatment has serious energy consumption, and the energy consumption accounts for about 35% of the total energy consumption[4]. This paper takes a batch of heat treatment process system as an example to analyze. The heat treatment process system includes three processes of normalizing, quenching and annealing, each process comprises two heating furnaces. The heat treatment process system model is shown in Figure 1.

![Figure 1. Heat treatment process system model](image)

Due to the different powers of different types of heating furnaces, the quality of the furnace charging directly affects the heating time and system heating energy consumption. In the heat treatment process, the forgings after each heat treatment process can be regrouped and combined to achieve a reasonable distribution of the quality of each furnace charging process, and at the same time, the volume of the furnace is controlled, and the furnace charging capacity difference rate is reduced to a minimum in the quality constraint, thereby achieve the maximum production capacity of the heat treatment system, maximize the furnace charging and save heating energy consumption. The regrouping scheduling model after each process is shown in Fig. 2.

![Figure 2. Reorganization and distribution of heat treatment process at each stage](image)

3. Quality Distribution of Furnace Charging under Maximum Heat Treatment Capacity

According to Fig. 1, the heat treatment system comprises normalizing, quenching and annealing. In each process, there are two heating furnaces with different specifications and parameters, and the heat treatment of the same batch of forgings is heated in two heating furnaces at the same time. To facilitate the model study, the following assumptions and regulations are made:

1) The heating of the last batch of forgings does not affect the use of the next batch. That is, when the batch of forgings completes the normalizing into the quenching process, the quenching process of the last batch of forgings is completed, and the quenching furnace is ready.
2) Introduce the material flow concept and transform the discrete furnace charging model into a continuous furnace charging model.
3) The arrangement order of each process has no effect on the whole of the heat treatment system. The charging quantity of each heating furnace is only related to the parameters of each heating furnace in the system. The single heating furnace is affected by the parameters of other heating
furnaces in this process.

4) During the heat treatment process of the same batch of forgings, the quantity of forgings is fixed in batches, no new forgings are added at each stage, and no forgings are withdrawn.

The goal of the model is: after the heat treatment at this stage is completed, the forgings are regrouped according to the energy consumption and the furnace capacity constraint of the heating furnace of the next heat treatment process, the heat treatment system can achieve the maximum processing capacity and the least energy consumption under the constraints of the capacity and flow rate of the heating furnace. In view of the above analysis, the model of "minimum cost maximum flow" can be used for optimization solution.

3.1. Minimum Cost Maximum Flow Model Analysis

For the construction of the minimum cost maximum flow network model $G(V, E, U, C)$, its complete element[5-7] should be included:

- $V$: represents the node set, node $v_i$ represents the resource supply and demand entity, it’s necessary to include a starting point $v_s$ and a convergence point $v_t$, the difference between the inflow and the outflow of the intermediate node is 0;
- $E$: represents an arc set between nodes, connects nodes, and realizes the circulation of resources between nodes;
- $U$: represents the resource circulation capacity on the arc set, and $u_{ij}$ represents the capacity between the nodes $v_i$ and $v_j$;
- $C$: represents the cost of the unit resource circulation on the arc set, and $c_{ij}$ represents the cost between the nodes $v_i$ and $v_j$.

The “minimum cost maximum flow”, as an algorithm for developing an optimal scheme. The formal description is as follows:

Objective function:

$$\min \sum_{(i,j) \in E} c(i,j)f(i,j)$$  \hspace{1cm} (1)

Restrictions:

$$0 \leq f(i,j) \leq u(i,j), \forall (i,j) \in E$$  \hspace{1cm} (2)

$$\sum_{(i,j) \in E} f(i,j) - \sum_{(j,i) \in E} f(j,i) = b(i), \forall j \in V$$  \hspace{1cm} (3)

Among them, $i$ and $j$ represent network model nodes; $c(i,j)$ represents the unit transportation cost of the arc; $f(i,j)$ represents the resource circulation on the arc $(i,j)$; $u(i,j)$ represents the arc $(i, j)$ capacity upper limit; $b(i)$ represents the node net flux. If $b(i)>0$, the node is the source node. If $b(i)<0$, the node is the convergence node, and the intermediate node $b(i)=0$, The stream satisfied $\sum_i b(i) = 0$ is called a feasible stream.

![Figure 3. Example of minimum cost maximum flow network model](image-url)
of the flow on the arc \((i,j)\) as \(u_{ij}\), the flow value as \(x_{ij}\), and set the starting point of the network flow graph to \(v_1\) and the end point to \(v_m\). The maximum flow rate \(f\) from the start point to the end point is solved with the following rules.

Max \(f\) 
s.t. 
\[
\sum_{j=1}^{p} x_{ji} - \sum_{k=1}^{q} x_{ki} = \begin{cases} 
  f(i = 1) \\
  0 & (i = 1, 2 \ldots m - 1) \\
  -f(i = m) 
\end{cases} 
\] 
\(0 \leq x_{ij} \leq u_{ij}, (i, j) \in N\) \hspace{1cm} (4)

Use this formula as the algorithm for finding the maximum flow, and Lingo is used to solve the problem. The maximum inflow \(f\) set in the program should be less than the minimum cut set value. The minimum cutoff refers to the cutoff of the minimum cut set. In the network diagram, if the connection from one phase \(s\) to another phase \(t\) is logically completed by a set of arcs \(L\), after removing the set of arcs, there is no longer a way to connect from \(s\) to \(t\), then the set of arcs \(L\) is a group of cut set of the network graph, and the sum of the corresponding capacity values is the cutoff of the cut set (see the figure above), which is recorded as \(u(L)\):

\[
u(L) = \sum_{(v_i, v_j) \in L} u_{ij}\] 

\(f_{\text{max}} \leq u(L)\) \hspace{1cm} (5)

(6)

The maximum flow is obtained by the minimum cutoff, and the minimum cost is obtained on the basis of the maximum flow, and the concept of the residual network is again introduced. First of all, make sure that each path has a corresponding cost, and there is already a flow network composed of the initial feasible flow \(\{(v_i, v_j)\mid (i, j) \in N\}\) The flow value has not yet reached the upper limit, and some of the path flow can still increase, while others are already saturated. The solution to the residual network is as follows:

\[
u_{ij}(x) = \begin{cases} 
  x_{ij}, (i, j) \in N \\
  u_{ij} = x_{ij}, (i, j) \in N & (x_{ij} < u_{ij}) 
\end{cases}\] 

(7)

According to the indication of the residual network, constantly search for the minimum cost path from the starting point \(v_s\) to the ending point \(v_t\), and then add an augmented chain along the path to increase the flow value until all feasible chains are saturated. At this time, the route allocation scheme is the result of minimum cost and maximum flow.

3.2. Heat Treatment System Model Construction Analysis

According to the equipment parameters, the heating furnace bottom area \(m^2\), the charging capacity kg, the power (KW=KJ/h), the unit time productivity (experience value of production efficiency kg/h) are obtained, and unit energy consumption are finally obtained.

According to the model, each feasible chain consists of three path, however, since the forgings need to be recombined after completing a process, the path can be added between the two processes for correction according to the requirements. After obtaining the parameters of each heating furnace, the model network is constructed. On each arc \((u_{ij}, c_{ij})\) stands for (capacity upper limit, unit forging heating energy consumption). The recombination of forgings is carried out between node 1, 3 and 2, 4. Although heat treatment is not required, the node path is appropriately corrected due to the addition of work, and the correction amount is set to 200.
Table 1. Heating furnace parameter processing

| Heating furnace type | process     | Heating furnace bottom area m² | Unit bottom area & time productivity kg/(m²*h) | Maximum furnace charging kg | Power KW | Power consumption per hour KJ/h | Unit time productivity kg/h | Unit energy consumption KJ/h |
|----------------------|-------------|--------------------------------|-----------------------------------------------|-----------------------------|---------|-------------------------------|-----------------------------|----------------------------|
| RX3-30-9             | normalizing| 0.274                          | 100                                           | 200                         | 30      | 108000                        | 27.36                       | 3947                       |
| RX3-45-9             | quenching   | 0.485                          | 120                                           | 400                         | 45      | 162000                        | 58.2                        | 2783                       |
| WZ-75                | quenching   | 0.866                          | 135                                           | 350                         | 150     | 540000                        | 116.94                      | 4618                       |
| WZ-60                |             | 0.585                          | 150                                           | 210                         | 100     | 360000                        | 87.75                       | 4103                       |
| RJ2-35-6             | tempering   | 0.196                          | 110                                           | 250                         | 35      | 126000                        | 21.59                       | 5837                       |
| RJ2-40-9             |            | 0.283                          | 150                                           | 450                         | 50      | 180000                        | 42.39                       | 4246                       |

Calculation formula: \[ C(t) \cdot D(t) / F(t) = 3600*F(t) \]

\[ H(t) = C(t) \]

\[ I(t) = G(t)/H(t) \]

Figure 4. Heat treatment process capacity-cost network model

4. Model Solving
The established network model is solved by Lingo software programming. Through the results of the programming demonstration, it can be concluded that in the heat treatment system consisting of 6 heating furnaces in the three heat treatment processes, the charging scheme with minimum total energy consumption can be achieved when the system is running at full load. The optimal charging scheme is assigned as follows:

Table 2. The optimal charging scheme for the Lingo solution

| Path arc | Heating furnace type | Value |
|----------|----------------------|-------|
| F(s,1)   | RX3-30-9             | 160.000 |
| F(S,3)   | RX3-45-9             | 400.000 |
| F(1,2)   | WZ-75                | 350.000 |
| F(3,4)   | WZ-60                | 210.000 |
| F(1,3)   | Recombination        | 0.000000 |
| F(3,1)   | Recombination        | 190.000 |
| F(2,4)   | Recombination        | 240.000 |
| F(4,2)   | Recombination        | 0.000000 |
| F(2,T)   | RJ2-35-6             | 110.000 |
| F(4,T)   | RJ2-40-9             | 450.000 |

The optimized flow diagram obtained from the results is shown in Figure 5 below. The full load path is marked with a bold arc. At this time, the \( (u_{ij}, x_{ij}) \) represents (capacity upper limit, optimized flow value).
The specific processing steps are as follows:
1) For the two heating furnaces in the normalizing process, (s,1) RX3-30-9 furnace is put into in 160kg forgings, (s,3) RX3-45-9 furnace is put into in 400kg forgings;
2) When the forgings are taken out of the furnace after the normalizing, take out 190 kg of forgings from the heating furnace (s,3) RX3-45-9 and add them to the other batch. The remaining 210 pieces are placed in the heating furnace (3,4) WZ-60 in the quenching process, the additional batch is put into the heating furnace (1,2) WZ-75 for the full load operation, and both are subjected to a quenching process;
3) At the end of the quenching, 240 forgings were taken out of the (1,2) WZ-75 heating furnace, placed in the (4,t) RJ2-40-9 heating furnace together with another 210 pieces, and the remaining 110 pieces were loaded into (2,t) RJ2-35-6 heating furnace for tempering.

By grouping the furnaces in this way, the maximum energy consumption and maximum productivity can be obtained, the minimum energy consumption is 6861420KJ, and the maximum productivity is 560kg.

5. Conclusion
Forging billet and forging heating as the core heat treatment process in forging production, the utilization rate of heating furnace in the heating process directly affects the production efficiency of the forging process and the energy consumption of the heating process, which is an important link to achieve the improvement of energy saving. The maximum charging capacity of the furnace is subject to quality constraints. Each heating furnace has a charging quality limit. In this paper, through the analysis of the heat treatment process and the minimum cost of the maximum flow model to solve the process of the maximum furnace charging capacity, to achieve the maximum solution of furnace loading quality.

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