A Production Planning and Scheduling Method Based on Heuristic Rules for Forming-sintering Production System

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Abstract. The forming-sintering process is the bottleneck of the magnetic material manufacturing system in general, which restricts the overall output of the workshop. It is hard to formulate a production plan due to the complex constraints in such production system. In current research, the production planning control framework integrated with DBR (Drum-Buffer-Rope) concept oriented for forming-sintering process is designed. Moreover, a heuristic method considering the constraints of the magnetic material production process is proposed, which standardize and optimize the preparation process of the forming-sintering production plan. The practical application indicates that the heuristic method greatly reduces the number of WIPs, shortens the order manufacturing cycle, and improves the on-time delivery rate and the utilization rate of the sintering furnace, as compared with the current planning method of the enterprise.

1. Introduction

Due to the complexity of the magnetic material production process, some manufacturing processes are closely related and constrained, and the production planning of magnetic materials is extremely difficult to formulate [1]. At present, the production plan of magnetic material is mainly prepared by the planners based on experience, and each process’s plan is compiled independently, resulting in a rough plan, which is difficult to implement to actual production system and guarantee the order delivery.

The forming-sintering process is the bottleneck of the magnetic material production system, which restricts the overall output of the workshop. Due to the complexity constraints of the two processes, it is hard to formulate a manufacture plan. Through the rational design of the forming-sintering production planning method, it is possible to standardize the preparation process of the forming-sintering production plan, improve the utilization of bottleneck resources, and reduce the number of WIPs. There were few studies related to the production planning or scheduling of magnetic materials, only a few research work from Northeastern University focused on the forming-sintering process separately[2,3]. For example, Liu [2] focused on process constraints and planning rules, but did not conduct in-depth study on the overall preparation method of the forming-sintering planning.

Due to the high complexity of the magnetic material production planning problem, the heuristic rule method is more suitable for finding a satisfactory solution to the production scheduling problem. The rule was based on a summary of past experience and can provide a satisfactory solution to the problem in a shorter period of time. Literature [4-8] provided a reference for the selection of heuristic rules and inspirations for the combination of heuristic rules and other mathematical methods.
2. Current status of magnetic material production

The manufacture of magnetic materials is a typical multi-variety and small batch production mode, includes two major processes: powder preparation and magnetic core production[9]. There are four processes in magnetic core production, which are forming, sintering, grinding, separating[10]. The forming and sintering processes are two key processes for the production of magnetic core. The forming process is the first process of magnetic core production. The process requires a forming machine to shape the powder. The formulation of the forming production plan needs to consider the equipment capacity, constraints of the forming process, the powder inventory, as well as the roughcast arrangement constraints of the sintering process. Sintering is the bottleneck process for magnetic core production, and its equipment capacity limits the overall output of the plant. When formulating the sintering production plan, the main consideration is the arrangement of roughcast. The resources used in the sintering process are sintering furnaces, different heights in the furnace have different temperatures, different product types need to be placed at different layers in the furnace according to manufacturing requirements [11]. Therefore, it is necessary to arrange the products in groups before processing, that is, each layer is required to place with different products and fire into the sintering furnace simultaneously, the loading tool used for the arranged roughcasts is the pusher. At present, the production schedules of the two processes are formulated separately in actual production, and the products of the forming process cannot meet the requirements for the roughcast arrangement, resulting in too much buffering of the semi-finished products before the sintering process and lowly utilization rate of the sintering furnace. The utilization rate of the sintering furnace is an important index for the enterprise to measure whether the sintering blank is optimal. Therefore, the comprehensive optimization of the forming-sintering process is a significant way to improve the magnetic material production efficiency.

3. Control framework of forming-sintering production planning

There are many constraints between forming and sintering process. The production plan should consider a series of constraints, such as order delivery, customer priority, powder stock, equipment capacity, operation group capacity, product-mold correspondence, and roughcast arrangement rules. Planning solutions should determine the resource assignment for each process of each order, and the start/end time of each order. The strong constrained process characteristics require that the scheduling of these two processes should be considered together. Therefore, based on the DBR model[12], a control framework of forming-sintering production plan has been proposed. Figure 1 shows the control frame diagram of forming-sintering. Firstly, according to the order requirements and the roughcast arrangement constraints, the order grouping plan can be formulated, then, the roughcast arrangement plan can be pulled by the order grouping plan, finally, the forming production plan can be prepared according to the roughcast arrangement planning and the constraints in the forming production process. According to the above processes, the maximum output of the bottleneck can be guaranteed.

![Figure 1](image)

**Figure 1.** The control framework of forming-sintering production plan.

The production status of the forming-sintering process includes various constraints such as product, production capacity, inventory, and process. It is more complicated than the traditional mixed flow
production system. The traditional production models and scheduling algorithms are not suitable for solving this problem. After actual research and summary, this paper combines the production status of magnetic materials to establish a production model for magnetic material forming-sintering process, which considering delivery, powder inventory, equipment capacity, operation group capacity, process constraints and other constraints, and proposes a heuristic-based production planning method that can solve the production model.

4. Modeling of forming-sintering problem

4.1. Key elements

There are three key elements involved in this forming-sintering production planning problem:

1) Decision variables: the production quantity of the production order in a certain shift; The number of furnaces of a certain shift.

2) Target: minimize the production manufacturing cycle, produce higher priority products firstly.

3) Constraints

1) Order delivery constraint. The forming-sintering production schedule needs to meet the due date.

2) Powder stock constraint. The daily used powder cannot exceed the current stock.

3) Roughcast arrangement constraint. Different types of orders should be placed at different heights of the sintering furnace and fired at the same time.

4) Mold capacity constraint. There is only one pair of molds on the production site, and the same mold only can be processed on one machine in a shift. When there are multiple orders to select the same mold for processing, the maximum capacity that can be processed in a shift is the production capacity of one forming machine.

5) Forming machine selection constraint. Different forming machines can be equipped with different specifications of the mold. Firstly, the selected mold is determined by the product type, and forming machine is processed and produced according to the selected mold. Different types of forming machines have different production capacities and need to be selected reasonably according to the size of the order.

6) Operation group capacity constraint. The forming equipment is responsible for the workers in the operation group, and each worker can only operate one forming machine, so the maximum forming capacity per day is limited by the capacity of the operation group.

4.2. Planning model

Table 1 is the relevant parameters and descriptions required by the model.

| Table 1. List of parameter descriptions. |
|------------------------------------------|
| Subscript                               |
| $i, j$ Order number, $i=1,2,...I$         |
| $p$ Type of molding machine, $p = 1,2,...P$ |
| $a$ The type of mold, $a=1,2,...A$        |
| $k$ Powder type, $k=1,2,...K$             |
| $t$ Production days, $t=1,2,...T$         |
| Set                                      |
| $A_i$ The set of molds that can be used by |
| order $i$                                |
| $P_a$ Collection of molding machine $P$    |
| that can be used in mold $a$              |
| $I_k$ Collection of orders that need to use |
| powder $k$                               |
| Parameter                                |
| $h$ The length of time required for sintering |
| a pusher                                 |
| $l$ Number of order types                |
| $P$ Number of molding machine types      |
| $A$ Number of mold types                 |
| $K$ Number of powder types               |
| $T$ Planning cycle                       |
4.2.1. Decision variables. $M_{it}$: Indicates the modulus of the order $i$ produced on day $t$. $Y_t$: Number of sintering furnaces on the day $t$.

4.2.2. Model expression. Object function:

$$\min \sum_{i=1}^{I} Z_i L_i$$

Where:

$$Z_i = \begin{cases} 
1 & \sum_{t=1}^{T} M_{it} < M_i \\
0 & \sum_{t=1}^{T} M_{it} \geq M_i 
\end{cases}$$

s.t.

$$\sum_{t=1}^{T} M_{it} \geq M_i$$

$$\sum_{i=1}^{I} X_{ik} W_i M_{it} \leq F_{tk}$$

$$\sum_{i=1}^{I} X_{ip} M_{it} \leq C_p$$

$$X_{ip} = \begin{cases} 
1 & p_i = p \\
0 & p_i \neq p 
\end{cases}$$

$$a_i \in I_{a1}, p_i \in A_p$$

$$C_{min} \leq \sum_{i=1}^{I} M_{it} \leq C_{max}$$

The second term of objective function (1) represents: $Z_i$ in formula (2) is a parameter that reflects whether the production of the product meets the due date. If product $i$ can be completed on time, then $Z_i = 1$, otherwise, $Z_i = 0$. The first term of objective function (1) represents: minimize total tardiness in the planning cycle, orders with higher priority need to be completed first. Equation (3) represents: all orders must be completed within period $T$, $i = 1, 2 ... I$. Equation (4) represents: the amount of each powder used per day cannot exceed the stock of the powder on that day. $k = 1, 2, 3, 4; t = 1, 2 ... T$. Equation (5) represents molding capacity constraints. Equation (6) represents: the output of all orders using the forming machine $p$ on day $t$ cannot exceed the maximum capacity of the forming machine on that day. $p = 1, 2 ... P; t = 1, 2 ... T$. Equation (7) represents forming machine equipment selection constraint. Equation (8) represents the maximum forming capacity per day is affected by the operation group.

5. Algorithm implementation

Due to the complexity of the constraints, the intelligent algorithm is not suitable for this problem. The production planning algorithm based on heuristic rules can get a better solution at a faster rate and has a strong practicability.
5.1. Detailed rules
Based on a detailed analysis of the forming-sintering process, nine types of heuristic rules were established.

(1) Order sorting rules (R1)
1) According to the order delivery constraints, orders with the closest delivery date are preferred, in order to minimize the order tardiness.
2) If two orders have the same delivery date, the production orders should be arranged according to the order priority, in order to ensure the priority service of the important customers.
3) If two orders have the same delivery date and priority, the order with less demand modulus should be arranged first to shorten the production cycle. The specific rules are as follows:
   R1.1: IF \( d_i > d_j \), THEN prioritizing \( O_j \)
   R1.2: IF \( d_i = d_j \), \( C_i > C_j \), THEN prioritizing \( O_i \)
   R1.3: IF \( d_i = d_j \), \( C_i = C_j \), \( M_i > M_j \), THEN prioritizing \( O_j \)

(2) Roughcast arrangement and combination rules (R2)
Considering the roughcast arrangement requirements in sintering, the roughcasts arranged in the same batch need to include products that are processed in all layers of the sintering furnace. The layer of the sintering furnace is represented by \( n \), and the order to be placed in layer \( n \) is formed into a set. The process department will give the roughcast arrangement information table \( IT_1 \) according to the order arranged by the rule R1. Then, according to the table \( IT_1 \), the combined order is successively arranged for production. The formula expression is as follows.
   R2: IF \( OST_{R1} = \{O_1, O_2, O_3, \ldots, O_9, O_{10}, \ldots\} \), \( IT_1 = \{O_3, O_4, O_7, O_{10}, \ldots\} \), THEN \( OST_{R21} = \{O_1, O_2, O_6, O_9, O_{3, O_4, O_7, O_{10}, \ldots}\} \)

(3) Roughcast grouping rules (R3)
When making the sintering plan, according to the order information table and the roughcast arrangement information table \( IT_1 \), select the current unordered combined order at the front of the order list to be fired in a sintering furnace. The formula expression is as follows.
   R3: IF \( OST_{R21} = \{O_1, O_2, O_6, O_9, O_{3, O_4, O_7, O_{10}, \ldots}\} \), \( IT_1 = \{O_3, O_4, O_7, O_{10}, \ldots\} \), THEN \( Oven_1 = \{O_1, O_2, O_6, O_9\} \), \( Oven_2 = \{O_{3, O_4, O_7, O_{10}, \ldots}\} \)

(4) Sintering capacity calculation rule (R4)
There are \( F \) sintering furnaces in the sintering workshop, and each of them can fire all the magnetic cores. Each sintering furnace processes \( r \) pushers on average every day. After determining the roughcast arrangement method on the sintering furnace, the production modulus of a product can be multiplied by the number of pushers that can be sintered in the sintering furnace one day to calculate the production modulus of the product in one day. At the same time, the cycle that the order needs to be processed in the sintering process can be obtained. The specific rules are as follows:
   R4.1: On day \( t \), \( B_i = x \), \( (r \times x) \leq M_iS \), THEN \( M_{it} = r \times x \), ELSE \( M_{it} = M_iS \)
   R4.2: IF on day \( t \), \( B_i = x \), \( (r \times x) > M_iS \), THEN after the order is completed, the next order for sintering the layer is allocated.
Note: Ceil (\( x \)) is an integer function.

(5) Powder inventory inspection rules (R5)
The total weight required for a type of powder on a given day should less than the stock of that type of powder on that day. In this planning model, when the sintering production plan is scheduled, the number of moulded products per day has been determined. Therefore, the inventory of powder should be checked when making the sintering plan, in order to prevent the shortage of powder stock. The specific rules are as follows:
R5: IF $I_{tk}$ indicate the order set that required to use the powder type k on day t, THEN $\sum (M_{it} \times w_i) \leq F_{tk}, i \in I_{tk}$

(6) Production order splitting rules (R6)

After completing the roughcast arrangement plan of sintering. Determine the production sequence of sintering furnace and divide the orders into several transfer orders according to the production capacity of sintering furnace. Each transfer work order is the production work order of the day before the forming process, to achieve the goal of pulling the forming output completely by sintering demand. The specific rules are as follows:

R6: $O_{is} = T_{is} = \text{Ceil} \left( \frac{M_i}{M_{it}} \right)$

(7) Mold selection rules (R7)

Each order type should choose the corresponding mold. The specific rules are as follows:

R7: $a_i \in A_i$

(8) Forming machine selection rule (R8)

R8: $p_i \in P_a$

(9) Forming machine capacity constraint rule (R9)

The maximum daily production capacity of the forming machine varies according to the choice of the forming machine. The actual production capacity can not exceed the maximum capacity of the forming machine. The specific rules are as follows:

$$R9: \sum_{i=1}^{t} X_{ip} M_{it} \leq C_p, X_{ip} = \begin{cases} 1 & p_i = p \\ 0 & p_i \neq p \end{cases}, p = 1,2 \ldots P; t = 1,2 \ldots T$$

5.2. Forming-sintering production planning algorithm based on heuristic rules

The heuristic algorithm in this paper is based on the DBR strategy, which drives the whole production plan according to bottleneck production plan to ensure the maximum utilization of the bottleneck. According to the actual situation of enterprises, the first day’s output of forming was used as a raw material for the second day of roughcast arrangement, that is, there was a one-day buffer between forming and sintering. In the planning period T, the sintering plan need to be prepared according to the roughcast arrangement information table IT1 and the order sorting information table IT2. Firstly, after carrying out the forming capacity evaluation and the powder inventory evaluation, the sintering production work order information table is generated in units of days , and be used as input work orders for the forming schedule. The forming production plan should meet the demand of the sintering production work orders finally. The forming-sintering production planning steps are shown in Figure 2, the details steps are as follows:

(1) Order sorting stage

Step1: Sort all the orders that need to be processed by forming-sintering according to R1.1, get the sorted order sequence.

Step2: Sort the order sequence that obtained by Step 1 according to R1.2

Step3: Sort the order sequence that obtained by Step 2 according to R1.3

Step4: Obtain the roughcast arrangement information table IT1, sort the order sequence that obtained by Step3 according to R2.

(2) Production planning and scheduling stage

On the premise that the production order is sorted, the production-planning method for forming-sintering process based on heuristic rules has several steps:

1) Sintering planning stage:

Step1: Obtain the order sorting information table IT2 that was sorted already; t=2, indicate that the second day of the planning cycle T is the start date of the sintering roughcast arrangement plan

Step2: $F=f$, indicate that the available sintering furnace resources are f on day t.

Step3: According to table IT1 and IT2, obtain the orders that need to be processed by the current furnaces by R3.
Step4: Obtain the modulus of product i that can be sintered per pusher according to product’s size and arrangement, then determine the modulus of the product i be sintered one day by rule R4.1.

Step5: Correct the processed product results obtained by R3 according to R4.2.

Step6: Update sintering blanking schedule table, obtain product categories and production information in current plan day, and divide each planned order into multiple transfer orders by sintering’s daily production.

Step7: \( F = F - 1 \). Judge if \( F \) is 0, If yes, execute sequentially, otherwise get back to Step3.

Step8: Get powder stock information table, determine whether the powder stock meets the demand according to rule R5; If yes, execute sequentially, otherwise back to Step3 and change order sequence.

Step9: \( t = t + 1 \); If \( t \geq T \), execute sequentially. If \( t < T \), get back to Step2.

Step10: Formulate a sintering roughcast arrangement plan, obtain the sintering roughcast arrangement plan table IT3; generate the transport order by rule R6, and use the daily total transfer order as the production work order the day before the forming process plan.

2) Forming planning stage:

Step11: \( t = 1 \), indicate the first day of a planning cycle \( T \) is taken as the start date of the forming plan.

Step12: \( i = 1 \), indicate the first work order.

Step13: Obtain the forming process’s daily production information table (IT4), and select a feasible mold according to the rule R7;

Step14: Update the forming process’s production information table (IT4), which include the information of mold type, production modulus and so on.

Step15: According to the rule R8, select the type of forming machine.

Step16: Obtain the forming process work order schedule.

Step17: Judge whether the daily production capacity meets the production demand according to the rule R9; If yes, execute sequentially, otherwise, get back to Step13;

Step18: \( i = i + 1 \). Judge if \( i \) is larger than I, If yes, execute sequentially, otherwise, get back to Step13;

Step19: Update the forming-sintering process scheduling results;

Step20: \( t = t + 1 \). Judge if \( t \) is less than \( T \), If yes, execute sequentially, otherwise, get back to Step11;

Step21: End.

Figure 2. Flow chart of forming-sintering production planning.
6. Conclusion
In current research, a planning and scheduling problem in forming-sintering production environment is studied, and a heuristic method consisting of several optimal rules is proposed for the special planning problem. The following conclusions have been obtained after applying this method to a magnetic material production enterprise: (1) The method has a strong practicality and can be used to solve actual production problems in a short scheduling period. (2) It has a strong versatility. By summarizing the production characteristics and practical constraints of kinds of multi-process magnetic materials production planning problems, a comprehensive set of heuristic rules are established, which can be applied to most magnetic material production workshops. (3) The optimization performance is significant. It can be found that the overall output of the workshop has been greatly improved, the number of WIPs have been significantly reduced, the order manufacturing cycle has been shortened, and the production efficiency of the workshop has been greatly improved.

The heuristic concept can also be extended to the furnace grouping optimization problem in the entire material industry [13]. It is demonstrated that this method can make positive effect for the planning and scheduling decisions, i.e., shortening the order manufacturing cycle, reducing the number of WIPs, and improving the on-time delivery capability of orders.

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