Flexible gypsum mould applied in the mechanical system for blank of grouted ceramic handicrafts based on the radial movement of the sphere and connection by the principle of six-point positioning

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Abstract: In order to solve the problems of low production efficiency, poor quality of blanks, high labour intensity and inability to meet the market demand with the manual gypsum mould, a novel design of the gypsum mould to be applied into the automatic production of the planks was developed for ceramic handicrafts. This mould inherits the advantages of the manual mould with tenon–mortise connection and adopts six-piece combination. According to the spherical radial movement, the new mould opens and closes, mostly avoiding movement interference and significantly improving service life. The connection technique of ‘six-point positioning principle’ was proposed and adopted to embed the connection device of four side die pieces with manipulator, so as to realise the strength of gypsum die pieces and effectively connect with the manipulator. Based on the group technique, the standard eigenvector and norm for the grouping of geometric elements of target blanks were proposed to realise the grouping of many different kinds of blanks into a few number of groups with all the blanks. Within a group, the gypsum mould keeps the external geometric features and tenon–mortise connection unchanged, while the working cavity of different blanks only alters, for the flexibility of gypsum mould. Thus, the universality of the mould is gained, and the design and manufacturing efficiency is greatly improved, with the considerable reduction of the cost, and the digitisation of design, manufacturing and management processes is realised. The gypsum mould provides a new technological method and technical guarantee for changing the labour-intensive production mode of ceramic handicraft blank cast and forming, realising the intellectualisation and automation of the main production link of ceramic handicraft blank cast and efficiency automatic and intellectualised production of ceramic handicraft blank with high identity.

1 Introduction

At present, the production process of ceramic cast blanks, especially ceramic handicraft blanks, mainly includes stirring preparation oar → mould closing → grout → dry → clean oar → solidify → demoulding and taking parts and so on. The basic production method is still in the state of manual operation, which is labour-intensive with high labour intensity of workers, it has low productivity and high cost, the quality of the blanks is unstable and the identity is poor. Blank quality mainly depends on the experience and skills of workers, not suitable for modern production and organisational management, incapable of meeting the growing market demand. Therefore, it is necessary to improve the manual gypsum mould or design a novel mechanical gypsum mould.

Lin et al. [1] presented the potential of gypsum as a candidate for rapid tooling used in injection moulding. The ingredients for the gypsum mould were decided upon, and an additional compression with a vibration process was introduced to enhance the mechanical strength of the gypsum mould. Christopher Ibeh et al. [2] put forward an X-ray CT study of miniature clay sample preparation techniques; the clay soil sample was prepared from slurry and either consolidated using an oedometer or a gypsum mould for improvement of the sample. Blazutti Marçal et al. [3, 4] aimed to present slip casting as a processing route for producing hydroxyapatite struts, and show the thermal phase stability, with gypsum mould. Daosheng Wen et al. [5] fabricated processing and mechanical properties of Si3N4 ceramic turbocharger wheel. A composite technique was chosen to fabricate Si3N4 ceramic turbine wheel based on modified investment casting, slip casting and mould constraint hot isostatic pressing aided by a near-net dimension using the gypsum mould and multi-piece Y₂O₃ ceramic mould. Daniel Drdlik et al. [6] focused the modification of the gypsum mould to limit Ca²⁺ contamination and to maintain favourable sucking properties with addition of cement to a standard gypsum mould to suppress its erosion, and a decrease in the sucking rate was observed due to its reduced macroporosity. Takaaki Nagaoka et al. [7] prepared alumina ceramics from a slurry with cellulose nanofibers with the gypsum mould, resulting in Al₂O₃ green bodies with no cracks could be prepared after demoulding and drying in air. Liu et al. [8, 9] researched the application of gypsum composite concrete in the antique building bracket set, with component design, mould making, pouring and conserving concrete of the bracket set which was made by gypsum concrete, and production process of assembling and installing, construction and installation methods were introduced, which will give some theoretical basis and technique reference to the application of the gypsum composite concrete in the antique architectural bracket set. Hwang and Kim [10] presented injection mould design of reverse engineering using injection moulding analysis and machine learning. Fu and Ma [11] proposed a method
to predict early-ejected plastic part air-cooling behaviour towards quality mould design and less moulding cycle time, integrating Moldflow (TM) and Ansys (TM) by feeding Moldflow (TM) simulation results as the intermediate state dataset into Ansys (TM) for air-cooling effect simulation. Fomina and Stolboushkin [12] developed a novel mould design for manufacturing of hollow ceramic products from coal wastes, with investigations of granulometric, chemical, mineral compositions and technological properties of waste from coal ar Billie enrichment and clay raw materials.

The current research focused on the analysis and design of ‘the machined ceramic handicrafts mould’ for change of ceramic arts and crafts body grouting moulding labour-intensive production mode to ceramic arts and handicrafts cast into intelligence and automation of the production, design a set with a machine with ceramic crafts plaster mould, to provide quality and efficient automatic and intelligent production parts technical support.

2 Tenon–mortise joint and the spherically radial movement principle of the gypsum mould for cast blank

2.1 Inherity of the traditional technology and creation of innovative tenon–mortise connection

In traditional manual handicraft blacking, the number of mould pieces depends upon the size and complexity of the black to cast, widely used mould pieces of the connection between ‘the tenon and mortise joint structure’, that is on the mating surfaces of the two connected surfaces with big size that is produced by adjacent two mould piece side long surface of uneven ‘bite’ (a mould piece that protrudes with tenon, and the cooperative mould piece with mortise, and the two meet together for a joint or a connection). In the grouting process, rubber bands are used to fix each die piece together to resist the grouting tension.

The structure of and tenon–mortise is well occluded and the plaster on the joint is permeable to each other, which ensures sufficient water absorption function. For this, we appropriately reduce the embedding angle, reducing the original 20° to 15°. At the same time, the opening and closing sequence of each die is controlled in sequence and each die is fixed with an elastic fixing sleeve. This not only ensures the machine use of gypsum mould, but also improves the reliability and service life significantly.

2.2 Linear movements along the spherically radial direction for opening and closing the mould

Take the spherical centre as the origin and the motion along the ray as the basic motion form of mould opening and closing. Take cube as the basic geometric structure; a six-piece universal gypsum mould was constructed with cylinder as the basic side piece. Traditionally manual operation of gypsum mould, according to the difference of mortise and mortise design and production process, according to experience and trial type sequential assembly, time consuming and laborious, and the face and corner wear serious. In addition, the number of die pieces of a complete mould, as little as two pieces, more than five, six pieces, even seven, eight pieces, lack of uniform standards and versatility. In this study, based on the combination of module motion according to the direction of spherical radial motion.

As shown in Fig. 1, the motion of the die is designed to move linearly along the direction of the ray according to the spherical centre as the origin. This not only ensures the safety and reliability of each die piece or several die pieces in the process of opening and closing without interference, but also minimises the friction between the die pieces, so as to improve the service life of the die (Fig. 2). A piece of the side die is presented with a connector for the manipulator in Fig. 3.

3 ‘Complete positioning + auxiliary support’ lining connector, based on ‘six point positioning principle’

In view of the gypsum curing strength value being about 10 MPa, mechanical movement and contact strength do not support the mould directly connected with the driven steel components. Therefore, the high strength, light and wear-resistant alloy sheet material is supposed to use both in the design and in production of gypsum mould as a plug embedded in the gypsum mould. The basic performance of water absorption and drying of the gypsum mould should not be affected. The embedded metal parts are firmly connected to the gypsum mould while some of these parts are open to the outside world, ensuring an effective and reliable connection with the manipulator connector (Fig. 4).

4 Design of mould flexibility and versatility with GT

Traditional manual mould can be ‘a mould with any change’, that is, any size or shape of the parts change, even if the change is local, small, all need a specific mould to design, neither adaptability nor versatility.

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![Fig. 1](image1.png)

**Fig. 1** Spherical centre as the origin and the motion along the ray as the basic motion form of mould opening and closing

![Fig. 2](image2.png)

**Fig. 2** Composition of six die pieces of machined ceramic mould

20 is upper die; 21 is side die 1; 22 is side die 4; 23 is side die 3; 24 is side die 2; 25 is bottom die

(a) Spherically radial open–close movement; (b) Six surfaces of the cube; (c) Six sides of the cylinder

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On the basis of group technology, keep the overall shape of the mould unchanged, various blank parts to be manufactured are grouped into a limited number of large groups, each of which contains several blank parts of similar size and shape. Then select the basic geometric elements and thickness size of gypsum mould, according to the specific large group, and the working cavity is supposed only to change to complete the design and production of gypsum mould of different blanks in the same group. The specific principle and method are as follows.

In the \( n \)-dimensional Euclidean space with real number, for \( m \) different blacks, they can be divided into \( K \) groups, \( K \leq m \). If the basic features of the blank (including size and shape) can be expressed in terms of

\[
F_{ij} = \{f_{i1}, f_{i2}, \ldots, f_{ij}, \ldots, f_{imK}\}, \quad i = 1, 2, \ldots, m; \quad j = 1, 2, \ldots, K
\]

and then

\[
F_{rk} = \{f_{r1}, f_{r2}, \ldots, f_{rk}, \ldots, f_{rK}\}, \quad k = 1, 2, \ldots, K
\]

represents the assumed standard eigenvectors within the group, then the norm

\[
|F_{rk} - F_{ij}| = \sqrt{\sum_{j=1}^{K} (f_{ij} - f_{rk})^2} \leq \varepsilon, \quad j = 1, 2, \ldots, K.
\]

In this equation, \( \varepsilon \) is a tiny positive number. If any of \( F_{ij} \) satisfies (3) then it becomes into a group. This brings great convenience to the design and manufacture of gypsum mould. Within the same group, only are the mould cavity changed, without any other alteration on the overall dimensions and outside structural parameters. As a result, any black belonging to the group can easily be realised in design and manufacturing, so that the process efficiency of design and manufacturing is greatly increased with the benefit of generality, the corresponding cost considerably greatly reduced.

5 Mould constituents and logic action sequence of the gypsum mould pieces

The mortise-tenon structure of the die provides a guarantee for the casting and forming of ceramic mixture during the closure of gypsum mould and casting operation after mould closure. Forces and deformations in the horizontal, vertical or the third direction or radial direction of the sphere provide a reaction. However, in the process of mould closing and opening, it is necessary to ensure that the straight line is used strictly according to the radial die piece, and the mould closing or opening is supposed to carry out orderly. At the last moment of mould closing, there should be adaptive fine tuning, so as to realise the complete connection and tight fitting of the working surface of mould cavity. Therefore, the opening and closing sequence needs planning.

Suppose that the die group is composed of \( n \) die pieces, and the mortise and tenon structure of the die pieces is shown in Fig. 5. There are at least one or two mortises and tenons on each of the four mating surfaces, the corresponding mate surfaces are four, and possibly connected with this die is other four surfaces belonging to other four different dies.

The assembly sequence constraint has specific requirements at design time. The definition and description of the whole system of gypsum mould are as follows:
Mould-composite:
\{Name, Shape, N, Mould-component (i, j, conc.k, conv.k), mate(r)\}
Name: name of a Mould-composite
Shape: the geometric form of the Mould-composite in profile
N: the number of Mould-components of which the mould-composite consists
Mould-component (i, j, conc.k, conv.k), i = 1, 2, 3, … N; k = 1, 2
Mate(r): constraints or mate condition in order, r = 1, 2, … P
r = 1, one mortise in the middle of the mate surface
r = 2, one tenon in the middle of the mate surface
r = 3, one mortise in the up-middle of the mate surface, and one mortise in the low-middle of the mate surface
r = 4, one tenon in the up-middle of the mate surface, and one mortise in the low middle of the mate surface

So, there are a sequence of the mould components:
Mould-component (i, j, conc.k, conv.k), i = 1, 2, 3, … N; k = 1, 2

Sequence planning of assembly logic sequence meeting constraint requirements: ensuring smoothness (non-interference) and rapidity (optimisation with the shortest time)

\[
T = \sum_{i=1}^{N} a_i t_i
\]

\(a_i\) is the time weight of the \(i\)th mould component; \(t_i\) is the basic time spent on the closure of the \(i\)th mould component.

The main influencing factors on the time of closure of the mould
(a) the time for the manipulator to return from the original position of the die to the fastening sleeve properly works out to band all the pieces of the die into a complete and firm mode, \(t_f\)
(b) time difference between the two adjacent mould components to mate, \(t_d\)
(c) time for the mould to flexibly move with peristalsis for complete closing, \(t_{peri}\)
(d) allocated time for closure of the mould from the production takt, \(T_p\)

The simultaneous operation time of each die shall only be calculated once, and the simultaneous operation time of other dies shall be removed from the total time.

Assume that the average motion speed of the bottom die and the upper die are \(x_1\) and \(x_6\) respectively; and the motion speed of the corresponding side dies are \(x_2, x_3, x_4\) and \(x_5\) respectively, when viewing the die components from the top to the bottom.

Die time: \(t_{fo}\)

According to the sequences and corresponding times, the optimal formula is obtained as follows:

Objective
\[
\min t_{fo} = \sum_{i=1}^{6} \alpha_i t_i 
\]  
(4)

\(t_i = x_1/x_1, \quad t_2 = x_2/x_6, \quad t_3 = x_3/x_2, \quad t_4 = x_4/x_3, \quad t_5 = x_5/x_4, \quad t_6 = x_6/x_5\).  
(5)

Constraints
\[
\sum_{i=1}^{N} \alpha_i t_i \leq T
\]

Side die life
\(T_{di} \leq 60 \times t_i, \quad i = 1, 2, \ldots, 4\)

Life for upper die and bottom die
\(Tub_{di} \leq 100 \times t_j, \quad j = 1, 2\)

Decision variables \(X \geq 0\).

6 Rigid and flexible connection between manipulator and the side dies
6.1 Connection requirements and solutions
Connection between the manipulator connector and the gypsum mould side die connector is given in Fig. 6.

6.2 Realisation method and mechatronics device
The tenon–mortise structure and radial movement of the die pieces require accurate movement, while the movement and power of each die come from the arm of the robot. Therefore, the current study focuses, besides the above issues, the design of a connector between the gypsum mould and the manipulator for the above functions. One solution is shown in Fig. 6.

The manipulator arm 55 can move in a horizontal direction. When it is connected with the connector of the side die piece of the gypsum mould, the arm moves in the direction of the connector. The electromagnet 56 is charged to make the push rod 57 fixedly connected with the coil, move left to press against the elastic

Fig. 5 Six pieces of dies and tenon–mortise structure
(a) Six pieces of dies, (b) Tenon–mortise structure
working edge 59 of the connector of the robot arm and make the compression spring 54 compress. When the position sensor (1) 551 sends a signal indicating that the horizontal movement of the arm connector is in place, the horizontal movement stops. Then the arm connector starts upward movement. When the position sensor (2) 593 hints that the arm connector vertical movement is in place, the vertical motion stops. The electromagnet 56 is off, push rod 57 returns, and compression spring 54 stretches, driving the flexible working edge of the manipulator arm connector rotate around the hinge from the \( \beta \) angle position to the \( \alpha \) angular position, meanwhile the working edge of the manipulator arm connector 59 contacts and then offsets tightly with the working plate (2) 51 of the side die piece. In a specific structure with both the two pieces connected as a whole, the motion of the side die piece completely obeys the robot arm.

For separation, the electromagnet 56 receives the command to energise, and the front push rod 57 is pressed against the elastic working edge 59 of the robot arm connector, making the compression spring 54 compress, resulting in the separation of the elastic working edge 59 of the robot arm connector and the working plate (2) 51 of the side die connector of the gypsum mould. The robot arm connector moves down to the designated position and stops; the robot arm connector moves horizontally to the designated position and stops. At this point, the connector of the robot arm and the connector of the side die of the gypsum mould are separated completely—a whole cycle is done.

6.3 Sequential action for open–close process of mould and flexible peristalsis for finally precise close of mould

The tenon and the mortise are dependent on each other, and the convex and concave connecting surfaces fit together, making the whole set of components of the mould be able to bear more external forces. The plaster modules are assembled according to the principles of mortise and tenon. At the moment before the final formation of the whole mould, each mould piece shall perform a sequential ‘flexible peristalsis’, so that the bonding surfaces and contact surfaces between the mould pieces can further fit, thus forming a ‘complete mould’ accurately and reliably.

The principle and method of mould opening are the same as above, but the sequence of action of each mould die piece is opposite to that of mould closing.

7 Conclusions

In order to solve the problems of low production efficiency, poor quality, poor identity and high labour intensity, which cannot meet the market demand, a gypsum mould for ceramic handicraft was proposed and designed. This mould inherits the advantages of manual mould tenon–mortise connection, improves the design and adopts six-piece combination mould components. According to the radial movement of the ball, it adopts smaller mortise–tenon joint slope and avoids the motion interference to the greatest extent and improves the service life of the mould, so as to meet the requirements of automatic and intelligent production of the ceramic handicraft production.

The connection technology of ‘six-point positioning principle’ is put forward and adopted to embed the connecting device with the manipulator into each side die with complete positioning and auxiliary support, which not only guarantees the strength of the plater die, but also realises the effective connection between the plater side die and the manipulator, providing technical support for the automation and intelligence of mould opening and closing.

Based on group technology, a so-called standard feature vector and a norm of geometric elements of the mould are proposed for the group, realising the blank production of many different types and sizes with a small number of group wares. Within a group, the gypsum mould keeps the external geometric features and tenon–mortise joint connection unchanged, and only alters the working cavity, fulfilling the mechanism and flexibility of the mould with standardisation. With this, the even better generality, design and manufacturing efficiency are greatly increased, and the corresponding cost reduced, benefiting the digital design, manufacturing and management processes.

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