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Method for near-net forming of a sand mold with digital flexible extrusion technology

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Abstract: In order to further improve the precision forming efficiency of a sand mold digital patternless casting and reduce the amount of sand mold cutting, a method for near-net forming of the sand mold with digital flexible extrusion technology was put forward. The theory, optimization algorithm and technology for sand mold near-net forming were studied. Experimental results show that the sand mold forming efficiency can be increased by 34%, and the molding sand can be reduced by 44%. The method for near-net forming of a sand mold with digital flexible extrusion technology can effectively promote the application of digital patternless casting technology in the mass production of castings and thus greatly improves the efficiency and automation of sand mold manufacturing.

Key words: patternless casting technology; near-net forming; sand mold; flexible extrusion technology; geometric packing

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As one of the main methods to obtain blank mechanical products, casting is an important technology of both mechanical and manufacturing industries serving as foundations in the fields of automobile, petrochemical, steel, electric power, etc.[1-2]. Traditional sand mold forming and casting technology features a long technological process, a low degree of automation, a large amount of timber consumption and serious environmental pollution. The long period of mold manufacturing restricts the development and production of castings. The lower manufacturing precision and efficiency of castings lead to a large amount of cutting and other problems [3].

With the rapid development of technology and the implementation of the global strategy for sustainable development, casting technology is generally developing towards excellent cleanliness, patternless application, high efficiency, digitalization, and environmental protection[4]. Sand mold digital patternless casting technology merges at this moment [5-7]. Wooden or metallic molds, used during sand mold manufacturing are omitted in the sand mold digital patternless casting process. This technology not only saves a large amount of raw materials, but also shortens the development cycle of new products[8-12].

To realize fast and near-net forming of sand mold, shorten the sand mold cutting time, conserve the molding sand, binders and other materials, and to improve the molding efficiency and automation levels, the method for near-net forming of sand mold with digital flexible extrusion technology has been developed based on sand mold digital patternless casting technology, as shown in Fig. 1.

1 Method for near-net forming of sand mold with flexible extrusion technology

As shown in Fig. 2, the sand mold model is obtained from the casting's model. The digital flexible extrusion unit array of the sand mold is driven by the optimization algorithm to form the sand mold model with the array's envelope surface. Then, by filling sand, solidifying sand mold, resetting unit array, the near-net forming sand mold is obtained.

1.1 Theory for sand mold near-net forming

The optimization algorithm for near-net forming of a sand mold with flexible extrusion technology can obtain the maximum volume of the envelope body by optimizing the rotation angle and position of the CAD model of the sand mold cavity on the initial plane of

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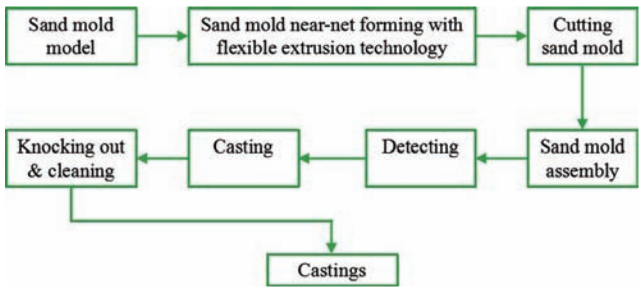


Fig. 1: Process of sand mold near-net forming and digital patternless casting

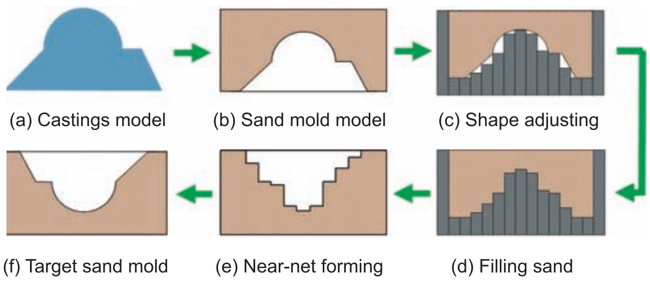


Fig. 2: Principle for digital flexible forming of sand mold

the flexible extrusion unit array. Based on this algorithm, the flexible extrusion unit array is force to make the units filling the sand mold cavity to the maximum extent. Then, the digital flexible extrusion technology creates the sand mold near-net forming.

In discrete geometry[13], if there is a set family $\widetilde{C} = \{C_1, C_2, \cdots, C_i, \cdots, C_n\}(1 \leqslant i \leqslant n)$ and a region D composed of convex bodies in the 3D space, and if $U_i C_i \subseteq D$ and any two convex bodies therein have no public interior point, then $\widetilde{C}$ is considered the packing of one geometric set family of D.

If D is a bounded area, then the density of the set family $\widetilde{C}$ relative to D can be defined as follows:

$$d(\widetilde{C}, D) = \frac{\Sigma_i V(C_i)}{V(D)} \times 100\% \qquad (1)$$

The region D is enclosed by the binary non-negative function $g_1(x,y)$ and o-xy plane. If the convex body set family $\widetilde{C}$ is made up of a cuboid C_i with the piecewise interval of the constant piecewise function $g_2(x,y)$ as the base and with the minimum function value corresponding to the piecewise interval of the constant piecewise function $g_2(x,y)$ as the height, then $U_i C_i \subseteq D$. If any two cuboids have no public interior point, then $\widetilde{C}$ is called as one cuboid sequence packing of D.

The degree of $U_i C_i$ approximation to D depends on the base size of the cuboid C_i. A larger base size of the cuboid C_i leads to a lower degree of $U_i C_i$ approximation to D. A smaller base size of the cuboid C_i leads to a higher degree of $U_i C_i$ approximation to D. When the cuboid C_i base tends to zero, the degree of $U_i C_i$ approximation to D should be 100%.

1.2 Flexible extrusion unit array of sand mold

Based on the research of a mathematical model for geometric packing[14], the flexible extrusion unit array platform was divided into $m \times n$ lattices. The physical model of the array is established with UG software. The curved surface of the target sand mold cavity is discretized. The mathematical model of the curved surface unit array with the discretized curved surface and the mathematical model of the cuboid array geometric packing were established.

From the definition of discrete geometric lattice, on the sand mold flexible extrusion platform, the m+1 intervals given along the x-direction are respectively parallel fixed vectors of **a**. The n+1 intervals given along the y-direction are respectively parallel fixed vectors of **b**. Therefore, such m+n+2 vectors can divide the sand mold flexible extrusion platform into $m \times n$ lattices, expressed as $\Lambda\,(u_{1x}, u_{2x}, \ldots, u_{mx}, u_{(m+1)x}, u_{1y}, u_{2y}, \ldots, u_{ny}, u_{(n+1)y})$.

The theory of discrete geometric lattice can be followed to establish the physical model of the sand mold flexible extrusion unit array, as shown in Fig. 3. All flexible extrusion units can be made telescopic to realize geometric packing of the sand mold cavity.

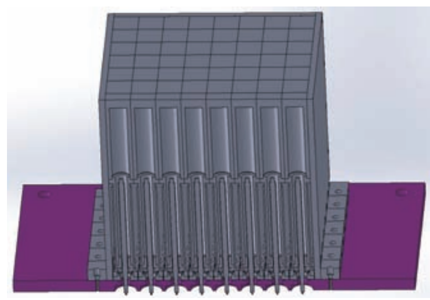


Fig. 3: Model for sand mold flexible extrusion unit array

2 Optimization algorithm for near-net forming of a sand mold with flexible extrusion technology

The optimization algorithm for near-net forming of a sand mold with flexible extrusion technology aims to optimize the position and posture of the sand mold CAD model to make the flexible extrusion unit array fill the sand mold CAD model cavity with the maximum extent.

2.1 Solution to cavity position based on random incremental algorithm

In the o-xyz coordinate system, an irregular casting is projected on the o-xy plane (in the mold joint). This casting is as a polygon enclosed by such points as A, B, C, D, E, F and G. As shown in Fig. 4, the sand mold cavity is projected on the initial plane (o-xy plane) of the sand mold digital flexible extrusion unit array. Therein, the digital flexible extrusion unit array is a $p \times q$ array. The working area is $a \times b$ for the upper plane of each extrusion unit. The working range is [0, H] in the z-direction.

The sand mold cavity projects along the negative z-direction towards the o-xy plane to the projection p. Namely, the closed plane geometric figure is surrounded by the polygon ABCDEFG. Moreover, the set P is the boundary points of projection p.

$$P = \{P_1, P_2, \ldots, P_i, \ldots, P_t\} \qquad (2)$$

where, i = 1, 2, 3,…, t.

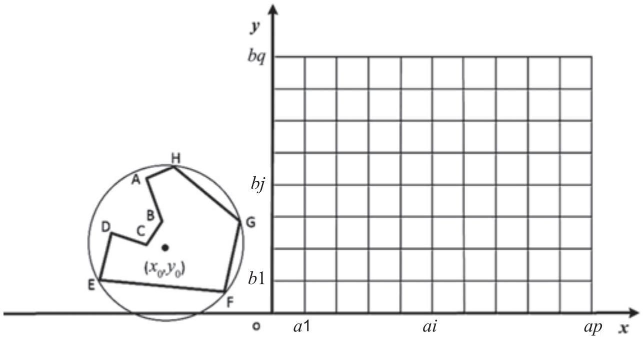


Fig. 4: Sand mold cavity projection and its minimum circumscribed circle

Based on the random incremental algorithm, the smallest circle C_t surrounded by the points in the set P and its center (x_0, y_0) can be obtained. The smallest surrounded circle C_t and its center (x_0, y_0) indicate the position of the CAD model cavity for the casting sand mold on the *o-xy* plane.

2.2 Optimization of sand mold near-net forming with digital flexible extrusion technology

Based on the working platform of the discretized unit array, an objective function satisfying the constraint conditions is established for optimizing the sand mold subject to digital extrusion.

2.2.1 Division of digital flexible extrusion working platform for sand mold

The surface function $f(x, y)$ represents the internal surface of the sand mold CAD model cavity. Its function value is not 0 within the area surrounded by the polygon $A_iB_iC_iD_iE_iF_iG_i$ but 0 beyond the area surrounded by the polygon $A_iB_iC_iD_iE_iF_iG_i$. Translate the projection p of the sand mold CAD model cavity along the vector **m** to the position (x_1, y_1), as shown in Fig. 5, to make its circumcircle center move from (x_0, y_0) to (x_1, y_1).

The working platform *o-xy* plane of the digital flexible extrusion unit array is discretized into $p\times q$ regions (secondary feasible regions). When the angle is rotated, the curved surface function can be expressed by Eq. (3):

$$f(x,y)_{|a} = \begin{cases} f_{1,1}(x,y)_{|a},\ x\in(0,\mathrm{a}1),\ y\in(0,b1) \\ f_{i,j}(x,y)_{|a},\ x\in[a(i-1),ai],\ y\in[b(j-1),bj] \\ f_{m,n}(x,y)_{|a},\ x\in[a(p-1),ap],\ y\in[b(q-1),bq] \end{cases} \tag{3}$$

where, $i,j\in Z$, $1\leqslant i\leqslant p, 1\leqslant j\leqslant q$.

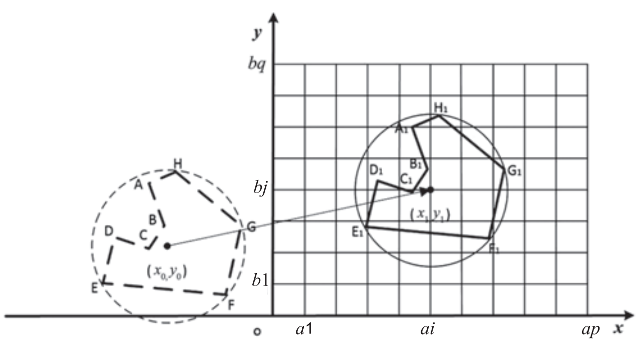


Fig. 5: Sand mold cavity projection translated to geometric center of initial plane

2.2.2 Objective function for optimizing sand mold subject

The angle rotation and position optimization of sand mold cavity are aimed to reduce the sand consumption and maximize the envelope volume of extrusion unit array. According to above targets, the sand mold cavity can have the regional model cavity optimized by translating respectively along the x and y-directions. The translation quantity is marked as X and Y when the rotation angle is α. The objective function is established as Eq. (4) for optimizing the sand mold digital flexible extrusion.

Max:

$$V(\alpha,X,Y)=\sum_{(j=1)}^{q}\sum_{(i=1)}^{p}\int_{b(j-1)}^{bj}\int_{a(i-1)}^{ai}[f_{i,j}([(x\text{-}X_0)\cos\alpha-(y-Y_0)\sin\alpha+X_0]-X,\ [(x-X_0)\sin\alpha+(y-Y_0)\cos\alpha+Y_0]-Y)_{\min|\alpha}]dxdy \tag{4}$$

2.2.3 Constraints for optimizing sand mold subject

On the condition that the sand mold CAD model can surely have its mold thickness in conformity with the requirements of the casting technical parameters, the cavity is rotated counter-clockwise at the angle of α around (x_1, y_1) on the initial plane. The extrusion unit array has its working platform characterized by central symmetry. So α has its value range as follows.

$$\alpha\in[0,180°) \tag{5}$$

At any angle α, the casting sand mold cavity has its position interval as follows:

$$\begin{cases} x_{r,k}\in(X_0-\frac{a}{2},X_0+\frac{a}{2}) \\ x_{r,k}\in(X_0-\frac{a}{2},X_0+\frac{a}{2}) \end{cases} \tag{6}$$

where, r=1, 2,…, m; k=1, 2,…, n.

Therefore, the constraint conditions should be as follows for optimizing the sand mold digital flexible extrusion:

$$\begin{cases} a\in(0,180) \\ X\in(-\frac{a}{2},\frac{a}{2}) \\ Y\in(-\frac{a}{2},\frac{a}{2}) \end{cases} \tag{7}$$

2.2.4 Solution to objective function for optimizing sand mold subject

On the condition that the constraint Eq. (7) is satisfied, the numerical iteration method is used to solve the objective function Eq. (4). The rotation angle and position of sand mold cavity are gradually optimized:

$$P_{(k+1)\ \alpha_{(r+1)}}=(X_{(k)},Y_{(k)})+s_{(k)}\,d_{(k)}\ {}_{|(\alpha=\alpha_{(r)}+s'_{(r)}d'_{(r)})} \tag{8}$$

where, r=0, 1,…, m; k=0, 1, 2,…, n; K is the iteration number of position; R is the iteration number of rotation angle; $s_{(k)}$ is the kth iterative step of position; $s'_{(r)}$ is the rth iterative step of rotation angle; $d_{(k)}$ is the kth direction of position; $d'_{(r)}$ is the rth direction of rotation angle; ($X_{(k)}$,$Y_{(k)}$) is the position of kth step; $\alpha_{(r)}$ is the rotation angle value of rth step.

The angle and position of the sand mold cavity, namely (α_{r_a},$X_{r_ak_a}$,$Y_{r_ak_a}$), are obtained, as shown in Fig. 6. The extrusion unit array obtains the largest envelope body.

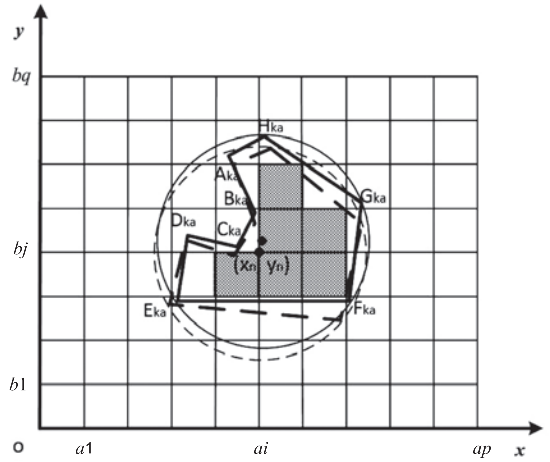


Fig. 6: Optimal solution of model cavity angle and position

2.2.5 Comparison of sand removal before and after optimization

When sand block is used for sand mold digital patternless casting directly, the volume of cutting molding sand can be expressed as Eq. (9). The volume is equal to the sand mold CAD model cavity.

$$V_0 = \int_0^{bq} \int_0^{ap} f(x,y)dxdy \tag{9}$$

When the CAD model cavity has its rotation angle and optimized position, as $(\alpha_{r_a}, x_{r_a}, _{k_a}, y_{r_a}, _{k_a})$, the top height corresponding to the digital flexible extrusion unit array can be represented as Eq. (10):

$$F(X,Y)\big|_{(a_{r_a}, x_{r_a, k_a}, y_{r_a, k_a})} = \begin{cases} F_{1,1}(x,y) = h_{1,1}, x \in (0, a1), y \in (0, b1) \\ F_{i,j}(x,y) = h_{i,j}, x \in [a(i-1), ai], y \in [b(j-1), bj] \\ F_{m,n}(x,y) = h_{m,n}, x \in [a(q-1), aq], y \in [b(p-1), bp] \end{cases} \tag{10}$$

where $i,j \in Z; 1 \leqslant i \leqslant p, 1 \leqslant j \leqslant q$.

When the near-net forming sand mold is used for the sand mold digital patternless casting, the removed volume of the cutting mold sand can be expressed as Eq. (11):

$$\begin{aligned} V_P\big|_{(a_{r_a}, x_{r_a, k_a}, y_{r_a, k_a})} &= V_0 - V(a,X,Y)_{max} \\ &= \sum_{j=1}^{q} \sum_{i=1}^{p} \int_{b(j-1)}^{bj} \int_{a(i-1)}^{aj} [f_{i,j}(x,y)\ a_{r_a} - F_{i,j}(x,y)]dxdy \end{aligned} \tag{11}$$

3 Case analysis

The analysis is made on the basis of a cylinder block (head), as shown in Fig. 7, and the upper sand mold of this cylinder head, as shown in Fig. 8.

3.1 Geometric packing of sand mold cavity

The upper sand mold is placed on the sand mold flexible extrusion unit array to optimize its angle and position, as shown in Fig. 9.

The lattices on the sand mold flexible extrusion unit array are translated along z-direction. The sand mold cavity surface

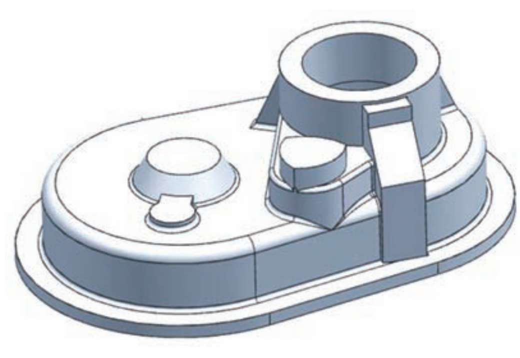


Fig. 7: Cylinder block (head)

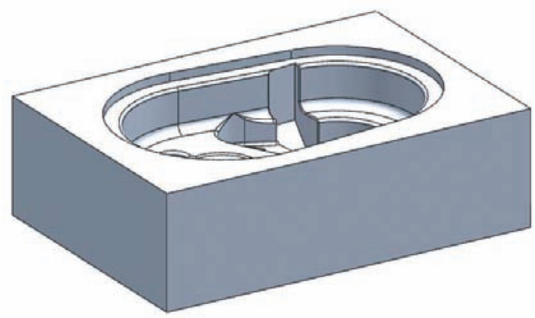


Fig. 8: Upper sand mold of the cylinder head

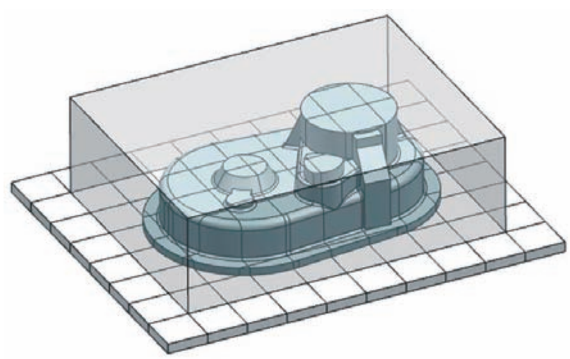


Fig. 9: Curved surface of target sand mold cavity

is divided into $m \times n$ discrete units:

$$g_{m,n}(x,y) = \begin{bmatrix} g_{1,1}(x,y) & \cdots & g_{1,j}(x,y) & \cdots & g_{1,n}(x,y) \\ \vdots & \ddots & \vdots & \iddots & \vdots \\ g_{i,1}(x,y) & \cdots & g_{i,j}(x,y) & \cdots & g_{i,n}(x,y) \\ \vdots & \iddots & \vdots & \ddots & \vdots \\ g_{m,1}(x,y) & \cdots & g_{m,j}(x,y) & \cdots & g_{m,n}(x,y) \end{bmatrix} \tag{12}$$

where, the feasible region of $g_{i,j}(x,y)$ is $\begin{cases} x \in [a(i-1), ai] \\ y \in [b(j-1), bj] \end{cases}$, $i,j \in Z$; and $1 \leqslant i \leqslant m, 1 \leqslant j \leqslant n$.

The target sand mold cavity is filled by the sand mold flexible extrusion units. The filling height is the minimum distance from the discrete unit to the platform of sand mold flexible extrusion unit array. When the packing is completed by extrusion units, the molding sand is filled into the space among the upper and side surfaces of the extrusion, as shown in Fig. 10.

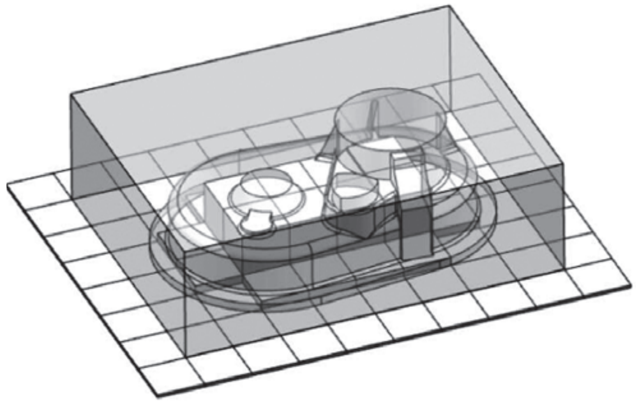


Fig. 10: Sand mold cavity geometric packing

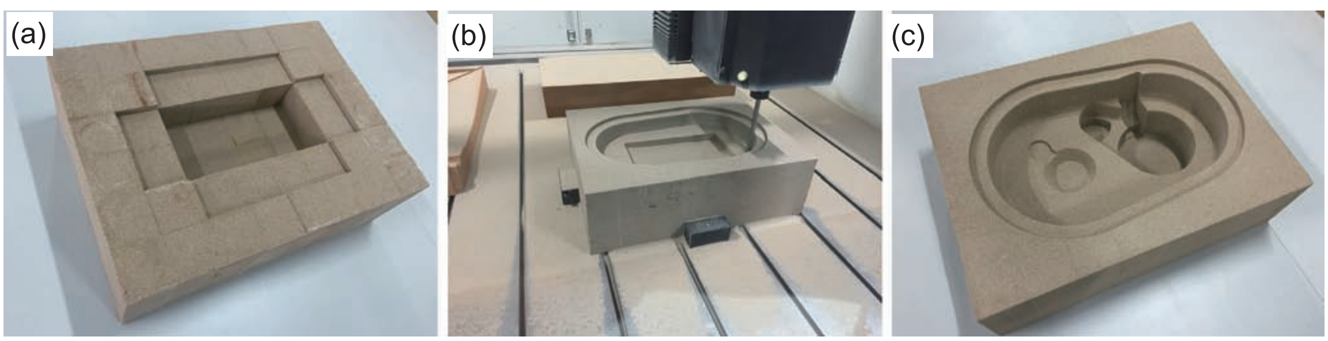
3.2 Test results and analysis

The CAMTC-SMS800 sand mold digital flexible extrusion forming machine is used for flexible near-net forming of the sand mold. This is to obtain a near-net forming sand mold through the working procedures of extrusion units adjustment, mold sand packing and sand mold curing. Then, the near-net forming sand mold is cut by the CAMTC-SMM1500S digital precision forming machine without a pattern to obtain the target sand mold.

Figures 11 (a), (b), (c) show the adjusted flexible sand box, the adjusted flexible mold and the curing process after sand packing. Figures 12 (a), (b) and (c) show the near-net forming sand mold, the precision forming process and the target sand mold after precision forming.

(a) Flexible sand box (b) Flexible mold (c) Curingprocess

Fig. 11: Process ofsand mold digital flexible extrusion near-net and precision forming



(a) Near-net sand mold (b) Precision forming (c) Target sand mold

Fig. 12: Process of the sand mold digital precision forming

The test results show that the sand mold flexible extrusion unit array can achieve near-net forming of the target sand mold. If the prefabricated near-net forming sand mold is used as the blank for digital patternless casting, it only takes 10,777 s cutting time, and 6.956×10^6 mm^3 molding sand is removed, while it would take 16,328 s if cut directly, and 1.582×10^7 mm^3 mold sand is removed with the sand block. In this case, the near-net forming sand mold cutting efficiency can be increased by 34% and with 44% molding sand saved.

4 Conclusions

This paper puts forward a method for near-net forming of sand mold with digital flexible extrusion technology. In order to achieve near-net forming of the target sand mold, the theory, optimization algorithm and technology for sand mold near-net forming have been studied. The experimental results show that sand mold forming efficiency can be greatly increased by 34% with the mold sand amount reduced by 44%. The technology has realized fast and near-net forming of sand mold, reduced the sand mold cutting during digital patternless casting, shortened the time for sand mold cutting, and achieved sand mold near-net forming with digital flexible extrusion. The technology can promote wide application of the sand mold digital patternless casting technology in mass production of castings. It can also greatly improve the high efficiency and automation of sand mold manufacturing.

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