DESIGN AND KINEMATICS ANALYSIS OF VERTICAL EXTERNAL MESHING BIOMASS PELLET FUEL FORMING MACHINE

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Abstract - In order to reduce the energy consumption of die roll forming machine and improve the productivity of piston punch forming machine, this paper proposes a new type of biomass solidification forming method. Firstly, a comparative analysis of the three types of biomass solidification forming equipment was carried out in terms of their working principles and performance, which revealed the characteristics of each type of biomass solidification forming equipment. Secondly, a new type of biomass pellet fuel forming machine was designed by combining the characteristics of piston punch forming machine and die roll forming machine. During operation, the plungers on the roller engage with the holes in the ring die, and the biomass material is continuously compressed and densely formed in the ring die holes, which reduce the energy consumption and improved the productivity. Finally, a kinematics analysis of the key components of the forming machine was carried out based on SolidWorks, and the feasibility of the design scheme was verified. The design of this forming machine can be a reference for improving the productivity and reducing the energy consumption of biomass solidification forming equipment.

Keywords: Biomass, Pellet fuel, Forming machine, External engagement, Kinematics analysis.

1. Introduction

Biomass solidification forming technology can compress the crushed agricultural and forestry wastes into block, rod and granular fuels (as shown in Figure 1) with a certain length and density under certain external force, temperature and humidity [1-3]. Biomass fuels have the advantages of convenient storage and transportation, high combustion calorific value and no pollution, which can be widely used in industrial boilers, power plants, residential heating, rural heating and so on [4-7].

Figure1: Biomass fuels

In order to improve the productivity and reduce the loss of energy consumption of the biomass solidification forming equipment, firstly, the working principle and performance of the biomass solidification forming equipment were compared and analysed. Secondly, the vertical external meshing biomass pellet fuel forming machine was designed based on the gear meshing principle. Finally, the kinematics analysis of the key components of the forming machine was carried out based on SolidWorks.

2. Comparison of Working Principle and Performance of Common Biomass Solidification Forming Equipment

There are three main types of biomass solidification forming equipment: screw extrusion forming machine, piston punch forming machine and die roll forming machine, among which die roll forming machine can be divided into ring die forming machine, flat die forming machine and double roll forming machine [8-9]. The working principle and performance of common biomass solidification forming equipment are not the same. Therefore, the working principle and performance of common biomass solidification forming equipment are compared and analysed as follows.

2.1 Working Principle of Common Biomass Solidification Forming Equipment

The earliest forming machine developed and applied is the screw extrusion forming machine, which mainly relies on the external heating of the forming die to maintain the forming temperature between 150℃ and 300℃. The biomass material is pushed and squeezed back and forth through the screw. Due to the forming temperature can soften the lignin and cellulose in the biomass material, so as to compress and compact into a block of biomass fuel. Its working principle is shown in Figure 2.

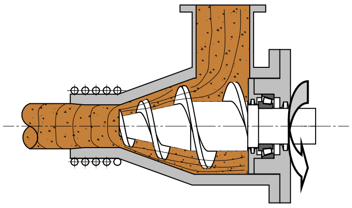


Figure 2: Screw extrusion forming machine

Compared with the screw extrusion forming machine, the piston punch forming machine usually does not need external heating. It mainly relies on the reciprocating movement of the piston to achieve the compression forming of biomass material. The forming machine is mainly used to produce solid block or rod fuels. According to the different types of driving forces, the piston punch forming machine can be divided into mechanical and hydraulic types. The mechanical type mainly uses the energy stored in the flywheel to push the piston to compress and shape the biomass material by using the crankshaft and connecting rod mechanism, while the hydraulic type is mainly powered by the hydraulic cylinder, which drives the piston to make the biomass material press into shape. Its working principle is shown in Figure 3.

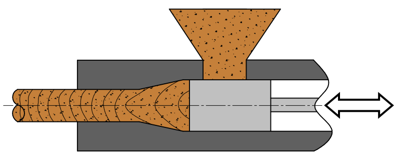
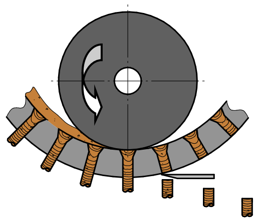
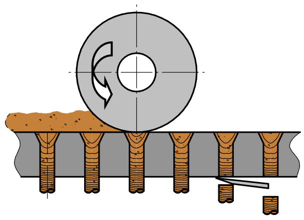


Figure 3: Piston punch forming machine

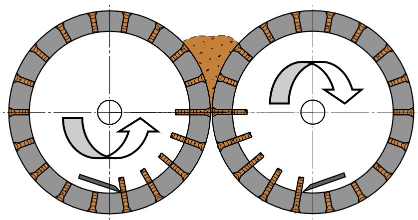
The die roll forming machine is mainly composed of two key components: the ring die (or flat die) and the roller. The roller generally rotates around its own axis, and its outer surface is machined with teeth or grooves, which is convenient for material pressing and can prevent slipping, while the outer surface of the ring die (or flat die) is machined with a certain number of forming holes. When the biomass material enters between the roller and the ring die (or flat die), then, due to the relative movement between the two, the biomass material is continuously pressed into the forming holes of the ring die (or flat die) and extruded. Because a cutting device is arranged at the outlet, the biomass particles with a certain length are cut under its action. The working principle of die roll forming machine with three structural forms is shown in Figure 4.



（a）Ring die forming machine



（b）Flat die forming machine



（c）Double roll forming machine

Figure 4: Die roll forming machine

2.2 Performance Comparison of Common Biomass Solidification Forming Equipment

Before the processing of biomass material, the screw extrusion forming machine needs to be heated and preheated, thus increasing the power consumption for producing each ton of biomass fuels in the extrusion forming process. Therefore, this type of equipment has the problem of high energy consumption. In addition, the output of this type of equipment is not high, which cannot meet the needs of actual production. At the same time, the main working component of the screw extrusion forming machine is the screw, and its service life shall not exceed 500 hours at most.

As the piston punch forming machine only extrudes the biomass material in the forming hole, its extrusion energy consumption is about effective energy consumption, so it has the advantage of relatively low energy consumption. However, because it can only realize the extrusion forming of biomass material once a time, it has the problem of low productivity. At the same time, the forming cavity of the piston punch forming machine is easy to wear, and it is generally repaired once every 100h, but some biomass material with less SiO_2 can last for 300h.

Compared with the first two types of forming machines, the die roll forming machine is evenly distributed with many forming holes on the inner or outer surface of the ring die. The roller can extrude the biomass material in multiple forming holes at the same time, so the productivity is greatly improved. However, the traditional die roll forming machine uses the outer curved surface of the ring die and the roller to extrude, therefore, the biomass material at the unopened position of the ring die are also squeezed unnecessarily, which results in additional energy loss and increases the energy consumption of the die roll forming machine.

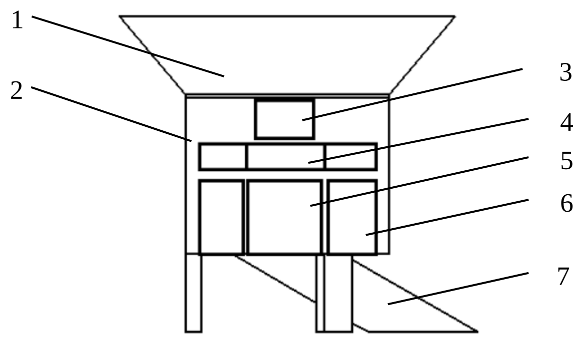
In summary, the characteristics of various types of biomass solidification forming equipment can be summarized as shown in Table 1.

Table 1. Comparisons of three kinds of biomass curing equipment

Equipment	Productivity	Energy Consumption	Abrasion
Screw extrusion forming machine	Low	High	Severe
Piston punch forming machine	Low	Low	Severe
Die roll forming machine	High	High	Severe

3. Design of the Vertical External Meshing Biomass Pellet Fuel Forming Machine

The vertical external meshing biomass pellet fuel forming machine is mainly composed of motor, gear transmission device, roller components, ring die components, inlet, outlet, box and so on. The design scheme is shown in Figure 5.



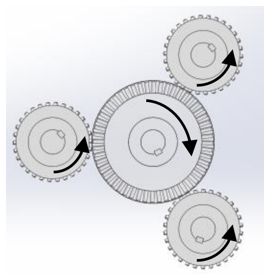
1.Inlet; 2. Box; 3. Motor components;
4. Gear transmission device; 5. Ring die components;
6. Roller components; 7. Outlet

Figure 5: Design scheme of forming machine

3.1 Working Principle of Forming Machine

The power provided by the motor is transmitted to the gear transmission device to realize the meshing movement of the big gear and the small gear. As the big gear is coaxial with the ring die, and the small gear is coaxial with the roller, the big gear and the small gear will be engaged and driven, and the ring die and the roller will rotate at the same time. The roller of the forming machine is different from the ordinary roller. A series of plungers are evenly distributed on the circumference of the roller. The roller and the ring die mesh with each other through the plungers and the forming holes, as shown in Figure 6.

After the material enters the box through the inlet, they fall between the ring die and the roller. The rotating movement of the roller and the ring die involves the material, and the material is squeezed into the forming holes by the plungers on the roller. Then, the roller and the ring die continue to rotate, and the plungers and the forming holes are gradually separated. Then the process is cycled. Every turn, the material is squeezed into the forming holes by the plungers. The material in the forming holes is constantly filled, and the loose material is compressed layer by layer. Each time, the material has undergone through several stages, such as compression, elastic deformation, plastic deformation and shape preservation. The material is extruded in the forming holes and plastic deformation occurs. Cellulose intertwines with each other and sticks closely, and adjacent particles are interwoven with each other. The residual stress between particles makes the combination more secure, and finally pellet fuels with a certain density and shape are formed at the outlet, as shown in Figure 7.



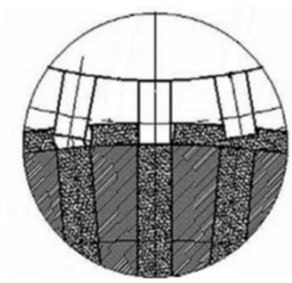


Figure 6: Working principle *Figure 7: Engaging part*

3.2 Technical Requirements of the Forming Machine

According to the design requirements, the vertical external meshing biomass pellet fuel forming machine shall meet the following formula,

$$i = \frac{n_1}{n_2} = \frac{N_2}{N_1} = \frac{d_2}{d_1} = \frac{z_2}{z_1} \quad (1)$$

Where, n_1 represents the speed of the roller, r/min; n_2 represents the speed of the ring die, r/min; N_1 represents the number of the roller plungers; N_2 represents the number of the ring die holes; d_1 represents the diameter of the engagement circle of the roller, mm; d_2 represents the diameter of the engagement circle of the ring die, mm; z_1 represents the number of the small gear teeth; z_2 represents the number of the big gear teeth.

Table 2. Technical requirements of the vertical external meshing biomass pellet fuel forming machine

Parameter	Value
Number of the roller plungers	150
Number of the ring die holes	260
Diameter of the engagement circle of the roller/mm	300
Diameter of the engagement circle of the ring die/mm	520
Number of the big gear teeth	30
Number of the small gear teeth	52

4. Design of Key Components

4. 1 Roller Components

The main energy consumption of the forming machine consists of the work done by the roller body to squeeze the raw material and the work done by the roller plunger to squeeze the raw material. Therefore, the most critical is the power consumed by the roller plunger to extrude the material in the extrusion forming area and the power consumed by the roller body to overcome the resistance of the material in the extrusion area. The power consumed by the roller plunger to extrude the material is as follows,

$$P_1 = knmp_0Av = \frac{\pi knmp_0 d^2 H}{4t} \quad (2)$$

where, k represents the simultaneous participation coefficient in the engagement process of the roller plunger; n represents the number of rollers; m represents the number of roller plunger rows involved in the engagement at the moment of engagement; p_o represents the maximum unit extrusion pressure of the roller plunger, MPa; A represents the cross-sectional area of the roller plunger, m^2; v represents the linear speed of the roller plunger, m/s; d represents the diameter of the roller plunger, m; H represents the extrusion length of the material, m; t represents the time required for each turn of the roller, s.

The power required for the roller body to overcome the resistance moment in the material extrusion deformation area is as follows,

$$P_2 = T\omega = 2\pi n_1 T \quad (3)$$

where, T represents the resistance moment of the roller body, N·m; ω represents the angular velocity of the roller, rad/s; n_1 represents the roller speed, r/min.

According to the comprehensive analysis of equation (2) and (3), the plunger roller structure can achieve the goal of reducing energy consumption. Figure 8 shows the structure of the plunger roller, which is mainly composed of the roller body and the plunger. In order to ensure the engagement relationship between the plungers of the roller and the holes of the ring die at the correct position, the plungers are evenly arranged in the circumferential direction on the outer surface of the roller. There are 30 rows of plungers on the roller, 5 in each row.

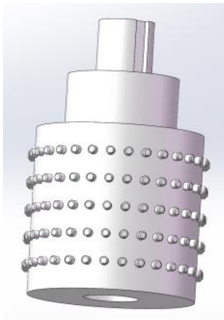


Figure 8: Roller components

4.2 Ring Die Components

As shown in Figure 9, the structure of the ring die is mainly composed of the ring die body and the ring die holes. The diameter of the ring die hole designed in this paper is 8mm. There are 52 columns, each column is arranged with 5, a total of 260 ring die holes are distributed around the ring die body. When there is movement interference between the roller plunger and the ring die hole, the forming machine cannot work normally. To avoid this situation, the inner surface of the ring die hole is provided with 45°×8mm chamfer.

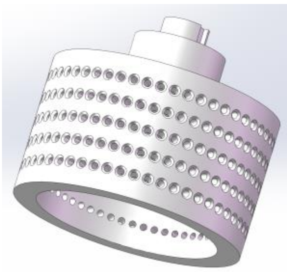


Figure 9: Ring die components

The engagement between the roller plunger and the ring die hole of the forming machine is the same as the gear engagement. The roller plunger and the ring die hole mesh each other to extrude the material forming. The material is gradually pressed by the roller plunger, and the density increases accordingly. After reaching the relative density, the material is shaped into a granular shape and discharged out of the ring die hole. In order to work normally, the roller plunger must overcome the friction force between the material and the ring die hole. The friction resistance is often closely related to the ratio of the length and diameter of the forming hole, and the greater the ratio, the greater the friction resistance. If friction is not overcome, the material cannot be squeezed into the forming hole and thus cannot be formed. Therefore, it is necessary to keep the ratio of the length and diameter of the ring die hole within a certain range. According to the experience, two sizes of ring die holes are designed here, and their length to diameter ratios are 4∶1 and 5∶1, respectively.

5. Design of Driving Part

The driving part of the forming machine is composed of motor, reducer, coupling, big gear, small gear and so on. The motor transmits the movement to the reducer through the coupling. The reducer reduces the output speed of the motor and transmits it to the big gear through the coupling. The big gear drives three small gears uniformly distributed around the circumference to rotate. As the big gear is coaxial with the ring die, and the small gear is coaxial with the roller, the big gear and the small gear will drive the ring die and the roller at the same time, and the roller and the ring die will mesh with each other through the plunger and the hole, as shown in Figure 10.

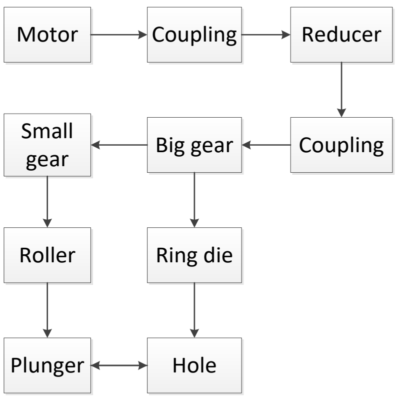


Figure 10: Workflow chart

5.1 Motor, Coupling and Reducer

Due to this paper mainly focuses on the structural design part of the forming machine, and the motor, coupling and reducer can be selected and purchased according to the actual needs, so this paper omitted the selection of motor, coupling and reducer.

5.2 Gear Transmission Device

The function of the gear transmission device is to transmit power between the power part and the working part, which is mainly composed of a big gear and three small gears. The big gear corresponds to the ring die, and the small gear corresponds to the roller, and they mesh with each other. The big gear transfers the power provided by the motor to the ring die shaft and three small gears, and finally realizes the movement of the ring die and the roller, as shown in Figure 11. In order to ensure the correct engagement of the roller plunger and the ring die hole, it is necessary to ensure that the reference circle diameter of the big gear and the small gear is equal to the engagement circle diameter of the roller and the ring die respectively, and the transmission ratio is equal to the number ratio of the plunger and the ring die hole.

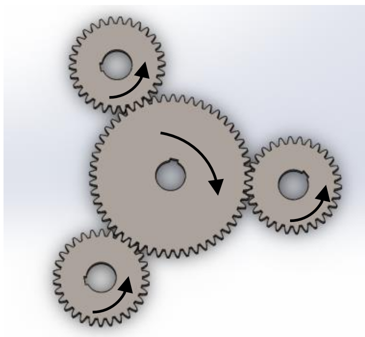


Figure 11: Gear components

(1) Design of small gear

The standard spur gear was selected, the modulus m was 10, the pressure angle α was 20°, the addendum coefficient h_a^* was 1.0, the tip clearance coefficient c^* was 0.25, and the number of teeth z_1 was 30.

Reference circle diameter

$d = mz = 10 \times 30 = 300mm$

Addendum circle diameter

$d_a = m(z + 2h_a^*) = 10 \times (30 + 2) = 320mm$

Root circle diameter

$d_f = m(z - 2h_a^* - 2c^*) = 10 \times (30 - 2 - 2 \times 0.25) = 275mm$

Tooth width b=100mm

Nominal shaft diameter d_x=100mm

(2) Design of big gear

The standard spur gear was selected, the modulus m was 10, the pressure angle α was 20°, the addendum coefficient h_a^* was 1.0, the tip clearance coefficient c^* was 0.25, and the number of teeth z_2 was 52.

Reference circle diameter

$d = mz = 10 \times 52 = 520mm$

Addendum circle diameter

$d_a = m(z + 2h_a^*) = 10 \times (52 + 2) = 540mm$

Root circle diameter

$d_f = m(z - 2h_a^* - 2c^*) = 10 \times (52 - 2 - 2 \times 0.25) = 495mm$

Tooth width b=100mm

Nominal shaft diameter d_x=100mm

Center distance

$a = \frac{1}{2}m(z_1 + z_2) = \frac{1}{2} \times 10 \times (30 + 52) = 410mm$

6. Virtual Prototype

According to the technical requirements in Table 1, a three-dimensional model of the forming machine was established based on SolidWorks software, as shown in Figure 12.

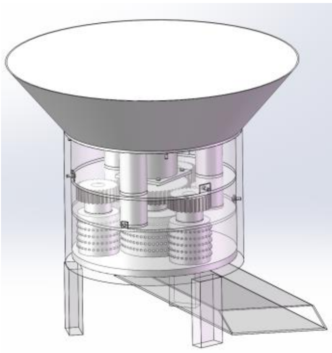


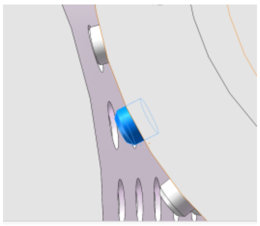
Figure 12: Vertical external meshing biomass pellet fuel forming machine

7. Kinematics Analysis

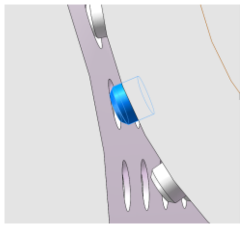
Different from the traditional forming machine, the forming machine adopts the forming mode of meshing between the roller plunger and the ring die hole, so it is also necessary to consider the motion interference between the roller plunger and the ring die hole, otherwise there may be collision or even stuck in the work. Referring to some literatures [10-16], this paper makes a kinematics analysis of the forming machine.

7.1 Motion Interference Analysis

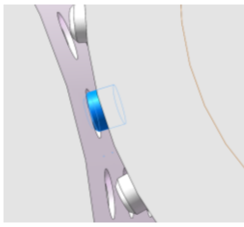
In SolidWorks software, three-dimensional models of each component are drawn according to the design requirements. After virtual assembly, motion interference analysis is carried out on the assembled solid model in the software to check whether there is any problem in the operation. First, select the plunger and hole that need to be engaged, and then adjust the positions to conduct interference check in the stages of non-engagement, initial engagement, full engagement, late engagement and the end of engagement respectively. It is found that the plunger and hole are well engaged without interference, as shown in Figure 13.



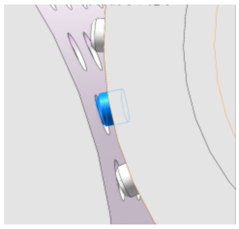
(a) Non-engagement



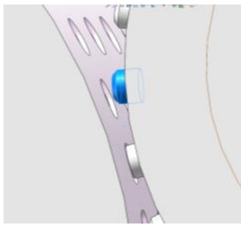
(b) Initial engagement



(c) Full engagement



(d) Late engagement



(e) End of engagement

Figure 13: Motion interference analysis

7.2 Motion Trajectory Analysis

7.2.1 Simulation Process and Parameter Setting

(1) Establish the three-dimensional solid model of the forming mechanism, as shown in Figure 14.

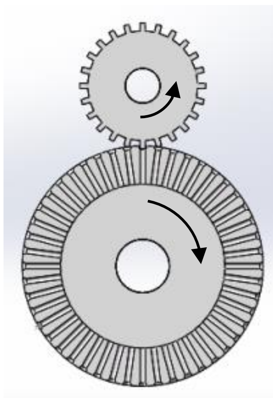


Figure 14: Three-dimensional solid model of the forming mechanism

(2) In the assembly interface, load the SolidWorks Motion plug-in, click Motion Study in the layout tab, and select Motion Analysis from the Type of Study in the Motion Manger toolbar.

(3) Click the Motor button in the Motion Manger toolbar to pop up the motor attribute manager. Apply a counter clockwise rotating motor with the speed of 20r/min to the shaft hole of roller and a clockwise rotating motor with the speed of 10r/min to the shaft hole of ring die, so that they can operate according to the actual situation.

(4) After completing the above settings, click the Calculate button to perform simulation solution.

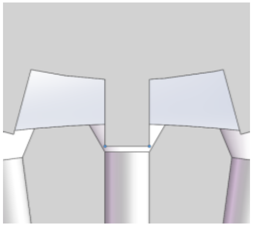
7.2.2 Simulation Results

(1) The motion trajectory of the roller plunger relative to the ring die hole

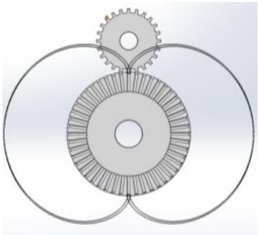
Figure 15 (a) to Figure 15 (c) show that the motion trajectories of the two key points on the roller plunger relative to the ring die hole are both cycloidal, and the motion trajectories are inside the ring die hole, and there is no overlap, so there is no interference between the roller plunger and the ring die hole.

(2) The motion trajectory of the ring die hole relative to the roller plunger

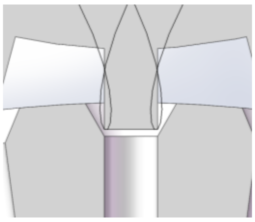
Figure 15 (d) to Figure 15 (f) show that the motion trajectories of the two key points on the ring die hole relative to the roller plunger are both cardioid, and the motion trajectories are outside the roller plunger, and there is no overlap, so there is no interference between the ring die hole and the roller plunger.



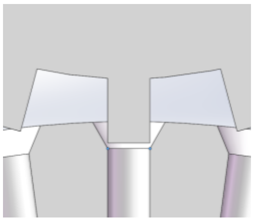
(a) Key points of the roller plunger



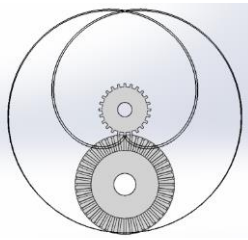
(b) Overall motion trajectory of the key points for the roller plunger relative to the ring die hole



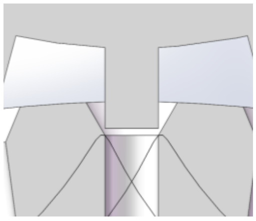
(c) Local motion trajectory of the key points for the roller plunger relative to the ring die hole



(d) Key points of the ring die hole



(e) Overall motion trajectory of the key points for the ring die hole relative to the roller plunger



(f) Local motion trajectory of the key points for the ring die hole relative to the roller plunger

Figure 15: Simulation results

8. Conclusions

Due to the different working principles of various types of biomass solidification forming equipment, they have their own advantages and disadvantages. How to overcome these shortcomings will become an urgent problem to be solved in the future. Developing a kind of biomass solidification forming equipment with low energy consumption, high productivity and strong durability of key components will become the future development direction and goal.

A new biomass curing forming machine was designed based on the principle of gear engagement, and the kinematics analysis of the key components of the forming machine was carried out based on SolidWorks, which verified the feasibility of the design scheme. The design of the forming machine can reduce the energy consumption of die roll forming machine and improve the productivity of piston punch forming machine.

Acknowledgements

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