Design Simulation and Structure Optimization of Plunger Assembly Closing

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Abstract. Hydraulic motors and pumps are the core components in hydraulic systems. The plunger assembly is a key component for the realization of the function of the axial piston pump and motor. The coupling between the slipper and the plunger body is completed through the closing process. With the application of computational science and finite element technology, DEFORM-3D metal forming process simulation is used to establish the corresponding closing device model of the plunger assembly. Through simulation, we analyze the change law of metal flow during plastic deformation process, and carry out structural optimization design based on the simulation results. We found that the closing is completed under the appropriate cone angle and distance line of the shoe, the quality is relatively uniform, and there is no closing defects such as metal flow overflow and cracks. The pull-off force and the clearance value after rolling can meet the design requirements. This method not only can effectively shorten the product verification cycle and reduce the cost, but also can reduce the defects of the finished product and improve the yield rate, providing a new way for the design of the closing structure and closing model of the plunger assembly.

1. Introduction
With the rapid development of modern airborne hydraulic technology, hydraulic systems have put forward higher performance requirements for hydraulic pumps and hydraulic motors. When the axial piston pumps and motors are working, the plunger assembly has to withstand the oil pressure, centrifugal force, inertial force, return force, friction force and the vertical reaction force of the swash plate, etc., which is the most complicated force in the axial piston pumps and motors. Therefore, the closing quality of the plunger assembly directly affects the life and reliability of the axial piston pumps and motors [1].

The quality index of the plunger assembly is: the size of the clearance between the plunger spherical
head and the slipper, and the size of the pull-off force. However, the size of the plunger assembly's clearance and the size of the pull-off are related to each other [2]. If the clearance of the plunger assembly is too large, the pull-off will become smaller, and if the clearance is too small, the movement of the plunger spherical head and the slipper will be inflexible, and the working conditions of the plunger assembly will become harsher.

This article introduces a plunger assembly closing device with the background of plastic forming CAE simulation technology. Using this device, the clearance value and pull-off force should meet the design value requirements, and there are no defects such as cracks, which has a good improvement in the life of the plunger assembly [3]. Therefore, it is necessary to simulate the closing process of the plunger to avoid excessive stress peaks and to seek the optimal closing design.

DEFORM-3D is a process simulation analysis software for 3D metal flow analysis of the metal forming process [1]. It integrates an automatic re-meshing generator that can be triggered when necessary to generate an optimized grid system, so that even if there are defects in the forming process, the simulation can be carried out to the end with high calculation accuracy [4]. The software has a rich material database and allows the input of materials that are not in the material library, making the software widely used in the field of forming analysis [5]. In this paper, based on DEFORM-3D's meshing ability and high calculation accuracy in plastic forming, a simulation model of the closing device of the plunger assembly is established, which provides a new method for optimizing the closing structure and the optimization design of the closing model.

2. Closing device and principle

The closing of the plunger assembly in this paper refers to the process in which part of the slipper convex platform (as shown in figure 1) deforms and wraps the plunger spherical head. There are two main types of closing methods: mold pressing closing and spinning closing. In this paper, mold pressing closing is used. Mold pressing closing is easy and efficient. The direction of metal flow follows the direction of friction force during closing, so the two spherical surfaces fit evenly after inclusion. The axial gap is small. The pull-off strength is high. And the closing process is more stable. The mold pressing closing has obvious advantages in the closing of small plunger assemblies. Figure 2 is a schematic diagram of the structure of the closing mold in this paper. Figure 3 is a schematic diagram of the mold pressing closing. The closing principle is as follows. The closing mold is fixed. The press moves downwards, and drives the plunger to move downwards. Because the plunger stiffness is far greater than the slipper convex, under the action of the plunger spherical head and the diversion groove of the closing mold, the metal flow of the convex part of the slipper is plastically deformed along the direction of the friction force to complete the closing of the plunger assembly.

![Figure 1. Schematic diagram of the convex part of the slipper.](image1)

![Figure 2. Closing mold structure.](image2)
3. Method of modeling and parameter setting

3.1. Modeling
The simulation models of the plunger, slipper and closing mold are imported into DEFORM-3D software. We adjust the contact relationship between each part model and fix their relative positions as shown in figure 4.

3.2. Calculation of material properties parameters
The material of the slipper is the alloy structural steel 25Cr3MoA, which has no similar properties in the DEFORM software material database, so the corresponding mechanical data of 25Cr3MoA material needs to be imported into the DEFORM software material database. The mechanical data of 25Cr3MoA used in this simulation are obtained from Jmatpro software, a powerful material property simulation software developed by sente software, UK. It is based on material type, and different material types correspond to different modules, which can be used to calculate various properties of metal materials.

The material composition of the metal 25Cr3MoA is tested. The mass fraction of its constituent mass components is entered into Jmatpro software, and the alloy material model is selected to calculate the material, which allows the Young's modulus, Poisson's ratio, density, shear modulus, flow stress-strain, metallographic diagram and thermal conductivity of the material to be obtained. Considering that the
closing simulation is carried out at room temperature, the heat generated during the process has little effect on the closing, so the heat transfer and thermal deformation of the closing process are simplified. The material properties data of 25Cr3MoA is shown in figure 5.
3.3. Material properties input

The above material properties data for 25Cr3MoA are imported into the DEFORM software material database. DEFORM software uses different methods to define the flow stress-strain model for different materials. There are various flow stress models available in DEFORM software. For alloy steel, the flow stress-strain model $\sigma = f(\varepsilon, \varepsilon_r, T)$ is very similar to the deformation behavior of 25Cr3MoA material, so it is used as the flow stress-strain model for this material, where $\sigma$ is the flow stress, $\varepsilon$ is the equivalent effect strain, $\varepsilon_r$ is the equivalent effect strain rate, and $T$ is the temperature.

The rest of the physical properties of the material: Poisson's ratio, Young's modulus, shear modulus and other data will not be repeated. The Normalized Cockcroft & Latham model is selected as the yield damage model, and the critical damage value is 0.45. After the data input is completed, the data is saved and the cold plastic forming model of the 25Cr3MoA material is established.

3.4. Pre-processing parameters setting

The material of the slipper is set to the imported 25Cr3MoA. It is tetrahedrally meshed, and the convex part is partially meshed by 0.2 times with a minimum length of 0.111mm, as shown in figure 6.
In this model, the plunger and the closing device are the upper and lower molds respectively, so they are both set as rigid bodies, where the plunger is the moving part in the model. In the process of metal plastic forming, there is plastic flow of deformed metal on the contact surface between the mold and the formed part in the model, and friction force is generated. Friction force is a complex physical phenomenon in this process, which affects the uniformity of the plastic flow and deformation of the metal, the size of the forming force, the surface quality of the formed part and the service life of the mold. In DEFORM software, three boundary friction models are provided for forming, namely shear friction model, Coulomb friction model and Hybrid friction model.

| Serial number | Structure | Codename | Name | Remarks |
|---------------|-----------|----------|------|---------|
| 1             | Slipper   | $L$      | The starting point of cone | Consider the relationship with center distance |
| 2             | Slipper   | $\beta^\circ$ | First cone angle | - |
| 3             | Slipper   | $\gamma^\circ$ | Second cone angle | - |
| 4             | Slipper   | $a$      | First cone distance | - |
| 5             | Slipper   | $b$      | Distance between second cone and top | - |
| 6             | Slipper   | $c$      | Diameter of the outer cylindrical surface of the closing | - |
| 7             | Closing mold | $x$ | Fillet distance | - |
| 8             | Closing mold | $\alpha^\circ$ | Fillet angle | - |
| 9             | Closing mold | $R'$ | Fillet $R'$ | - |
| 10            | Closing mold | $R''$ | Fillet $R''$ | - |
| 11            | Plunger   | $v$      | Closing speed | - |

In the forming process of the closing model under high load conditions, the contact surfaces of the plunger spherical head and the concave spherical surface of the slipper, the outer cone surface of the slipper and the closing device are all set as shear friction. In order to obtain the best control process of the closing, the variables of this model are the size of the cone angle of the slipper, the position distance of the segmentation curve, the parameter adjustment of the closing angle of the closing device, and the speed control of the closing process, as shown in figure 7 and figure 8. The description of the parameter variables is shown in table 1.
4. Simulation results

4.1. The influence of the slipper design on the closing results

According to the aforementioned simulation variables, in this closing model, the design variables of the slipper mainly affect the full wrapping of the closing and the size of the pressure. After sufficient simulation and comparison analysis, appropriate parameter variable values can be obtained. The slipper design model and the corresponding stroke pressure curve are shown in figure 9~ figure 11.

Figure 9. (a) Insufficient wrapping model and (b) Stroke pressure curve.

Figure 10. (a) Overflowing wrapping model and (b) Stroke pressure curve.
Figure 11. (a) Suitable wrapping model and (b) Stroke pressure curve.

From the above figure, it can be seen that too large or too small slipper cone angle and distance will affect the uniform wrapping of the closing. If it is too small, it will cause insufficient closing of the component and a large gap, failing to meet the designed pull-off force value, resulting in scrapping of components. If it is too large, it will increase the pressure during the closing process. The metal flow will overflow after closing. The quality of the closing will be uneven, which may even cause damage to the plunger spherical head. The closing quality of the closing under the suitable slipper cone angle and distance line is relatively uniform. There is no closing defects such as metal flow overflow and cracks. The pull-off force and the clearance value after rolling can meet the design requirements.

4.2. Pull-off force
Under the conditions of insufficient and suitable wrapping, a pull-off rate of 0.05 mm/s is applied to the closed plunger assembly. The pull-off model and pull-off force curve are shown in figure 12 and figure 13 respectively.

Figure 12. (a) Insufficient wrapping pull-off model and (b) Pull-off force curve.
From the results of figure 12 and figure 13, it can be seen that whether the plunger spherical head is fully wrapped after closing will directly affect the pull-off force of the plunger assembly. There is a proportional relationship, that is, after closing, without other defects, the more fully the plunger spherical head is wrapped by the slipper, the greater the pull-off force will be.

In summary, it can be concluded that the reasonable design of the slipper cone angle and distance is a prerequisite for the plunger assembly to meet the design value requirements after closing.

4.3. The effect of closing mold design on closing results

According to the aforementioned simulation variables, the second variable in the present closing model is the process parameters design of the closing contact angle of the closing device. The influence on the closing is mainly manifested as affecting the plastic flow of metal, the uniformity of deformation, the size of the forming force, the internal structure and surface quality of the formed part. Therefore, under the premise that the plunger assembly plunger spherical head has sufficient wrapping, the process design parameters of the contact angle of the closing device play a decisive role in the quality of the closing.

Comparison of the impact of different process parameters design of closing contact angle on the quality of closing, closing model and stroke pressure curve are shown in figure 14 and figure 15, respectively.
Figure 15. (a) Reasonable closing mold and (b) Stroke pressure curve.

By comparing figure 14 with figure 15, it can be obtained that, under the premise of suitable design of the closing of the slipper convex, if the design of the closing mold is unreasonable, the metal flow does not flow completely in the direction of the closing, and the metal flow is sheared out locally, so that the quality of the closing is poor, and its stroke closing pressure becomes large. Therefore, the reasonable design of the closing mold is also one of the prerequisites for the plunger assembly to complete the closing better.

4.4. The effect of closing speed on closing results

According to the aforementioned simulation variables, the third variable in this closing model is the change of closing rate. Based on the synthesis of the first two variables, a reasonable design size of the slipper structure and a closing mold with a reasonable structure will be obtained. The closing simulation will be carried out at different closing speeds. The stroke pressure at different rates of closing is shown in figure 16.
Figure 16. Stroke pressure when the closing rate is (a) 3mm/s, (b) 6mm/s, (c) 9mm/s, (d) 12mm/s and (e) 15mm/s.

As can be seen from the above figure, different closing rates have an effect on the closing stroke pressure. Under the same slipper structure and closing device, when the closing rate is less than 6mm/s, a relatively large sudden stress will be instantaneously encountered during the closing process, causing the pressure of the main mold to suddenly increase. When the closing rate is between 6mm/s~12mm/s, the pressure change curve of the main mold during the closing process is relatively gentle, and there is no obvious sudden change. And when the closing rate is greater than or equal to 15mm/s, a relatively large abrupt stress will also be encountered, causing the pressure of the main mold to increase.

5. Conclusion

Based on the DEFORM-3D metal forming process simulation, according to the setting of the plunger assembly closing quality influencing variables, the closing models are established separately. Through the simulation results of metal plastic forming under different variable conditions, the structural design is continuously optimized, and finally a reasonable closing device of the plunger assembly in this state is obtained. The disadvantage is that the temperature conditions are not considered in detail, but it provides a theoretical reference idea and method to solve the engineering problem of the plunger assembly closing.

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References

[1] HU J, LI X. (2011) DEFORM-3D Plastic Forming CAE Application Course. Peking University Press, Beijing.
[2] MENG L, HU C, ZHAO Z. (2014) Research progress of friction types in metal plastic forming. Die & Mold Industry, 40: 1-7.
[3] LIN X. (2000) Application of DEFORM-2D and DEFORM-3DCAE software in simulating plastic deformation process of metals. J. Mold Technology, 35(3): 75-80.
[4] SHI J, ZHU P et al. (2019) Stamping simulation of progressive die based on DEFORM. Modern Manufacturing Technology and Equipment, 000(012): 170-171, 173.
[5] LUO J, YUAN M. (2018) Development and application research based on DEFORM material database. Journal of Chongqing University of Technology (Natural Science), 2: 127-134.