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Study on the Effect of Process Parameters on the Density of PEEK Compression Moulding Based on Experiment and Simulation

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Abstract. Peek is a special polymer material known for its exceptional mechanical properties, stable chemical properties, high temperature resistance, self-lubrication, wear resistance, and fatigue resistance. Peek is extensively used in various fields such as aerospace, automotive, electrical and electronic, and medical equipment. It has emerged as the most popular high-performance engineering plastic due to its excellent properties and versatility. Therefore, it is crucial to investigate the impact of process parameters on the quality of peek materials. This research article presents a finite element model that investigates the impact of process parameters on compression moulding density. The model incorporates the compression equation and the Shima-Oyane yield criterion. The model was used to perform finite element simulations of compression moulding with different process parameters. The simulation results show that increasing the compression load within a certain range enhances the top punch's ability to overcome the interaction and friction between materials, resulting in increased forming density. By extending the holding time and improving the lubricant conditions, it is possible to not only increase the forming density, but also enhance the uniformity of distribution. This study lays the foundation for optimizing pressing process parameters and predicting future moulding results.

Keywords: finite element analysis, process parameters, relative density

1. Introduction

The advancement of warfare and weapons technology has led to an increase in performance requirements for weapons worldwide. Ammunition is a crucial component in warfare, and the loading process plays a significant role in its production. The quality of ammunition charge is directly linked to its precision strike capability and destructive power. Therefore, process and equipment are the critical determinants of ammunition quality.

Loading methods commonly used in industry include injection and press loading. The press loading method is widely preferred, where bulk granules are pressed through a die punch to form a pillar of a specific size and shape in a bomb cavity or cathode. This

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method results in a high forming density and has a short production cycle.

2. Experiments and Simulation

2.1 Experimental procedure and forming mechanism

Peek compression moulding is a process that involves forming loose particles in a moulding tool into a high density by applying pressure [1]. This research focuses on the one-way compress moulding process, which utilizes equipment consisting of a top punch, mould, and base (as shown in Figure 1a). During the compression process, pressure is applied solely to the top punch, which is the only part that moves at all times. The process consists of three stages: pressure-rising, pressure-holding, and unloading, as illustrated in Figure 1a, 1b, and 1c, respectively. During the press-rising phase, the pressure applied to the top punch gradually increases from F_i to the set value. At this stage, the peek is distributed relatively loosely in the mould, as depicted in Figure 1a. Compaction is primarily achieved by filling the voids in the mould through mutual sliding of the particles. Once the pressure-holding stage is reached, the pressure is maintained at a constant level. In this stage, the peek is distributed in the mould with varying density gradients, as shown in Figure 1b. Additionally, the material undergoes significant elastic-plastic deformation. Upon unloading and demolding, the forming billet is forcefully ejected from the mould due to the force of F_t, while the peek is fully compressed [2]. Due to the lack of restraint of the top punch at this stage, there will be a slight rebound of the billet resulting in a reduction in density. The experiment used a cylindrical mould with dimensions of 20 mm in diameter and 40 mm in height to fill the peek. Although the modulus of elasticity and Poisson's ratio of peek are not constant during the pressing process [3], their variations with relative density are shown respectively by the following equations:

$$\mu = \mu_0 \mathrm{e}^{-12.5(1-\rho)^2} \tag{1}$$

where μ_0 is the Poisson's ratio before pressing, ρ is the relative density of the pressed material.

$$E = E_0 \rho \tag{2}$$

where E_0 is the Modulus of elasticity before pressing, ρ is the relative density of the pressed material.

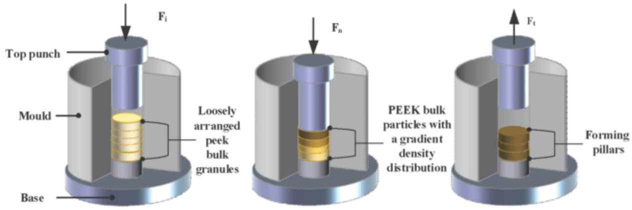


Figure 1. Equipment and process simplified diagram, (a) pressure-rising, (b) pressure-holding, (c) unloading

2.2 Establishment of Finite element simulation model

To efficiently and accurately analyze the influence of process parameters on the forming quality of peek, a 3D finite element simulation was established by MSC.Marc. The compacted material was originally a cylinder with a diameter of 20 mm and a height of 40 mm. To increase efficiency and reduce the number of calculation steps, a hexagonal mesh was used to subdivide the model, as shown in Figure 2.

The coefficient of friction between the material and the die wall is complex. It depends on a number of other parameters. For example, pressure, local density, die geometry and lubrication conditions. In this study, all contact bodies have been set to 0.15 [4].

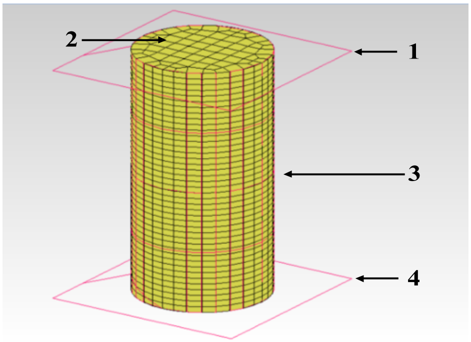


Figure 2. 3D model and grid division, 1. Top punch, 2. Pressed material, 3. Female mold, 4. Base

The compression moulding process involves pressing only the top punch while keeping the base fixed, resulting in a densely formed piece with specific strength and shape. During the process, the simulation model defines only the displacement and force boundary conditions, as the temperature remains constant. The displacement boundary condition restricts the movement of the top lunch punch in the non-motion direction, while the force boundary condition applies a concentrated force perpendicular to the cylindrical bottom surface [5]. This force varies in magnitude and direction over time and is applied to the top punch. During the pressure and pressure holding stages, load control is utilized to regulate the top punch, whereas stroke control is employed during the discharge stage to achieve discharge and demolding. The model's initial relative density is established at 0.6. The convergence judgement methods are the same for each stage, with residual force or relative displacement selected, and the relative residual force tolerance set to 1 and the relative displacement convergence tolerance set to 0.1. Bi-linear Coulomb friction is selected for contact control. The type of analysis is set to large strain analysis and the solution is solved using the updated Lagrange method [6].

For the quantitative equation of the relationship between pressure and relative density, it is necessary to take into account the non-linear hysteresis characteristics of the powder body and the large strain changes that occur. Huang proposes a double logarithmic compaction equation as shown in the following equation which provides a more accurate quantitative description for the unidirectional compaction model [7-8].

$$\lg \ln \frac{(\rho_1 - \rho_2)\rho}{(\rho_1 - \rho)\rho_0} = n \lg P - \lg M \tag{3}$$

Where ρ_1, ρ_0, ρ, P, M, n, respectively represents the material's theoretical density, initial density, pressure, elastic modulus, reciprocal of the hardening index.

Selecting an appropriate yield criterion is crucial for improving the accuracy of simulation results in stamping model development. This is because the material density changes constantly during the press forming process, and there is a functional relationship between the yield stress and relative density of the material [9]. In this study, the Shima-Oyane model is utilized as the yield criterion for materials, incorporating volume change, flow pressure, and static pressure. The equation for the yield function is expressed as follows [10].

$$F = \frac{1}{\gamma}\left(\frac{3}{2}\sigma^d\sigma^d + \frac{p^2}{\beta^2}\right)^{\frac{1}{2}} - \sigma_y \tag{4}$$

Where σ_y, σ_d, p, γ, β, respectively represents the uniaxial yield strength, stress component tensor, pressure, two material parameters related to the relative density and the expressions as shown in Eqs. (5), (6).

$$\gamma = (q_1 + q_2\rho_r^{q_3})^{q_4} \tag{5}$$

$$\beta = (b_1 + b_2\rho_r^{b_3})^{b_4} \tag{6}$$

3. Results

3.1 Experiment results

The press-formed billets, with a diameter of 20mm, were obtained by applying a pressure of 300 MPa for 2 seconds, followed by a holding time of 178 seconds. The experiment results are shown in Figure 3. And the scans conducted using a 225kV microfocus industrial CT revealed significant porosity at the edges of the die, particularly near the top punch and bottom as shown in Figure 4.

Figure 3. 20 mm diameter press formed billets

Figure 4. CT scan results

3.2 Simulation results

3.2.1 Effect of pressure

Figure 5 displays a clear segmentation pattern in the forming density variation. The result shows that increasing the pressing force improves the relative density of the molding within the range of 60~300 kN. However, the effect on relative density becomes weak and limited when the pressure load surpasses 157 kN.

In Figure 6, the density distributions and cures over time are displayed under different pressures. When examining the distribution diagram, it is apparent that the density is not uniformly distributed in the area where the top punch and base are in direct contact with the inner wall of the die due to friction between each contact body. However, the density is relatively uniform in the central part of the entire blank. Combining the density change curves of the feature nodes in each model reveals that density increases rapidly in the early stages of the pressing process and then gradually decreases. This pattern of variation is consistent with the displacement variation observed during pressing. As pressure is applied, it works to overcome the compression resistance between the materials and the frictional forces. Increasing the pressure can enhance the top punch's ability to conquer the compression resistance and friction, resulting in greater displacement and higher densities.

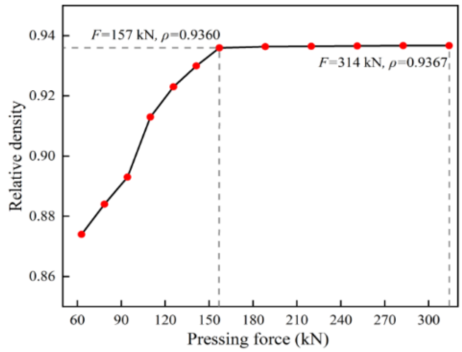
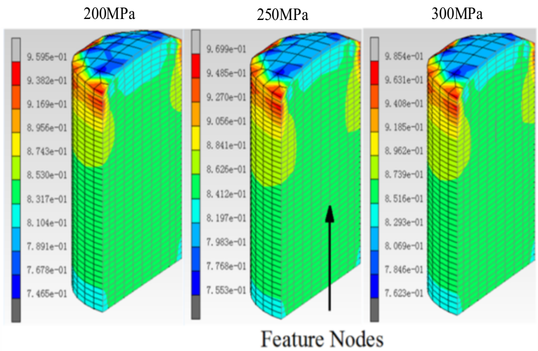
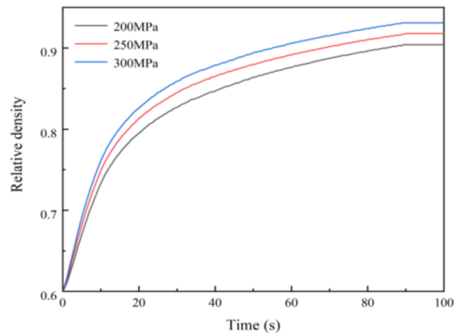


Figure 5. Relative density change curves at different pressing force



(a)



(b)

Figure 6. Simulation results under different loads, (a)Sectional density profile, (b)Density-time curves of different pressures

3.2.2 Effect of holding time

Numerical simulations were conducted by extending the holding time to various degrees, and the results are presented in Figure 7. The relative density of the blank increases with an increase in holding time within the range chosen for this study. This indicates that a greater amount of compressive load is transferred between the materials in the direction of compression. Increasing the holding time not only enhances the forming density, but also contributes to a more uniform distribution of density. The optimal holding time for achieving the smallest relative density difference is 120 s.

3.2.3 Effect of friction coefficient

The simulation model allows for direct modification of the coefficient of friction between the contact bodies. By improving the lubrication conditions during the experiment, the coefficient of friction can be reduced. Figure 8 presents the simulation results for various coefficients of friction. As the friction coefficient increases, both the maximum and minimum relative density decrease while the density difference increases. These findings suggest that the relative density inhomogeneity also increases gradually. Friction between the top punch and the material being pressed weakens the forming effect of the material. If the lubrication conditions deteriorate, it becomes difficult for the top punch to move in the pressing direction under the same pressing load, resulting in reduced displacement and relative density.

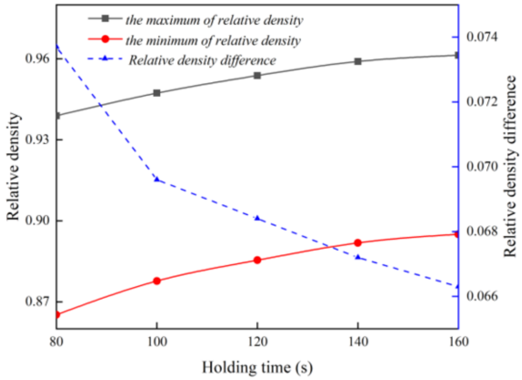


Figure 7. Relative density change curve at different holding time

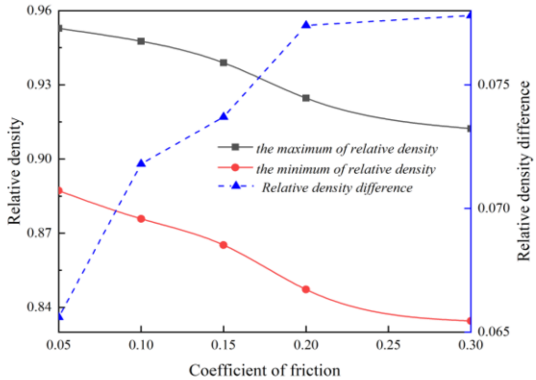


Figure 8. Densities under different coefficient of frictions

4. Conclusion

This study presents a finite element simulation model which accurately describes the compression moulding process of peek bulk particles. The model is based on the compression moulding mechanism and the Shima-Oyane yield criterion, and enables the study of displacement and density variation patterns during the pressing process. The paper focuses on the effect of different process parameters on the quality of compression moulding. The quality of the pressed material can be determined by its relative density at the end of the pressing process. Studies have shown that increasing the pressing force within a specific range can greatly enhance the quality of the moulded material. Additionally, prolonging the holding time and reducing the friction coefficient can improve both the relative density and the uniformity of the density distribution. Significant improvement in moulding density can be achieved by increasing the initial relative density of the material.

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