ISSN 2616-5767 Vol.7, Issue 3: 7-11, DOI: 10.25236/AJETS.2024.070302

Dynamics Simulation of the Forming Process of Seven-Hole Single-Base Propellant

Yulong Fang[1,a,*], Jingyu Zou[2], Bin Liu[1]

[1]Luzhou North Chemical Industries Co., Ltd., Luzhou, China
[2]School of Energy and Power Engineering, Nanjing University of Science and Technology, Nanjing, China
[a]yLongFang@163.com
[*]Corresponding author

Abstract: *Forming process is a key process in the manufacturing of propellant. In order to get insight into the flow behaviour during the forming process of 7-hole single-base propellants, this study conducted a dynamics simulation on the forming process based on fluid mechanics methods and finite element methods. The dynamic model of the 7-hole propellant forming process was solved using the PolyFlow finite element software, and the flow behaviour of the propellant inside the die is analysed and the forming quality is evaluated. Results show that the material flow in forming part exhibits a stable flow distribution, which is beneficial for the formation of the 7-hole propellant.*

Keywords: *Propellant forming; Numerical simulation; Forming dynamics; Quality evaluation*

1. Introduction

To ensure optimal ballistic performance of the propellant, it is essential for it to possess appropriate grain size and density. Therefore, in the manufacturing process of propellants, specific dies are employed to shape the propellant grains under certain pressure, giving them specific dimensions, shapes, and densities [1]. The quality of the forming process directly impacts the operational performance of the propellant.

In order to enhance the quality of propellants, researchers have conducted numerous studies on the forming process of propellants. Zhang and He [2] utilized PolyFlow software to conduct simulation studies on the propellant forming process, analyzing the effects of material proportions, temperature, and other parameters on the forming process of triple-base propellants. Liu et al. [3] used ANSYS software to investigate the material forming process of triple-base propellants, analyzing the impact of die structure on parameters such as pressure and velocity of the material during the forming process. The results indicated that the die contraction angle has a significant influence on the forming process of triple-base propellants. Zhu et al. [4] conducted a simulation analysis on the influence of wall slip effects on the forming process of nitroguanidine propellants. Ji et al. [5] carried out a simulation analysis on the impact of mold structure on the material flow field during the forming process of 19-hole propellants, and optimized the die structure. Ji et al. [6] and Lv et al. [7] also used computational fluid dynamics methods to analyze the effects of die structural parameters on the deformation of formed propellant cords. Chang et al. [8] studied the influence of die structure on the forming process of 11/7 nitroguanidine propellants by simulation, and analyzed the effects of different die structure solutions. Zou et al. [9, 10] conducted research on the forming process of single-hole energetic materials in the die contraction forming section and the complete die using finite element simulation software, analyzing the forming dynamics of single-hole energetic materials, the influence of kinetic parameters, and proposing an evaluation and optimization scheme for forming quality consistency.

This study conducted dynamic modeling of the forming process of single-base propellant in a 7-hole die based on fluid mechanics theory and Navier-Stokes equations. The model was solved using Ansys PolyFlow software based on the finite element method, and the dynamics of the forming process of the 7-hole single-base propellant was analyzed. The forming quality was investigated using the previously proposed forming quality evaluation method [9].

ISSN 2616-5767 Vol.7, Issue 3: 7-11, DOI: 10.25236/AJETS.2024.070302

2. Dynamics model

The geometric model of the forming channel for single-base propellant in a 7-hole die is shown in Figure 1, consisting of a contraction part, forming part and free part. The free part represents the formed propellant cord. Table 1 presents the structural parameters of the geometric model. The basic assumptions of the forming process are as follows: (1) the flow of the propellant material is incompressible steady flow and fully developed [11]. (2) the forming process is isothermal [9]. (3) the propellant material has high viscosity, neglecting inertia and gravity forces [11].(4) no slip on the walls [12, 13].

According to the basic assumptions, the governing equations of the dynamics model for the forming process based on the Navier-Stokes equations (including mass and momentum conservation equations) are provided below:

$$\nabla \cdot \boldsymbol{u} = 0) \tag{1}$$

$$-\nabla p + \nabla \cdot \boldsymbol{\tau} = 0 \tag{2}$$

where $\boldsymbol{u}$ is the velocity vector, p is the pressure and $\boldsymbol{\tau}$ is the stress tensor,

$$\boldsymbol{\tau} = 2\eta \boldsymbol{D} \tag{3}$$

where η is the material viscosity, and $\boldsymbol{D}$ is the deformation rate tensor,

$$\boldsymbol{D} = \frac{1}{2}((\nabla \boldsymbol{u})^{\mathrm{T}} + \nabla \boldsymbol{u}) \tag{4}$$

A successful numerical simulation requires realistic material model [9, 14]. The material parameters of the propellant were obtained through rotational rheology tests. The flow curve of the single-base propellant material is shown in Figure 2 (data sourced from reference [9]), and the viscosity-shear rate relationship is described using the Bird-Carreau model:

$$\eta(\dot{\gamma}) = \eta_{\infty} + (\eta_0 - \eta_{\infty})(1 + \lambda^2 \dot{\gamma}^2)^{\frac{n-1}{2}} \tag{5}$$

where $\eta(\dot{\gamma})$ is the current material viscosity, η_{∞} (the infinite shear viscosity), η_0 (the zero-shear viscosity), λ (time constant), n (the rheological index) are the material constants, and $\dot{\gamma}$ is the current shear rate obtained by

$$\dot{\gamma} = \sqrt{2tr(\boldsymbol{D})^2} \tag{6}$$

The parameters of the propellant rheological model are listed in Table 2. Considering the symmetry of the geometric model, a one-sixth model was selected for the study. The computational domain was discretized into hexahedral structured grids using Multizone technology. Figure 3 displays the mesh model of the forming process of the 7-hole propellant, consisting of 69,524 nodes and 63,040 elements.

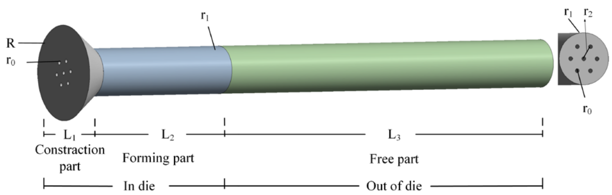

Figure 1: The geometry model of the forming process of 7-hole propellant.

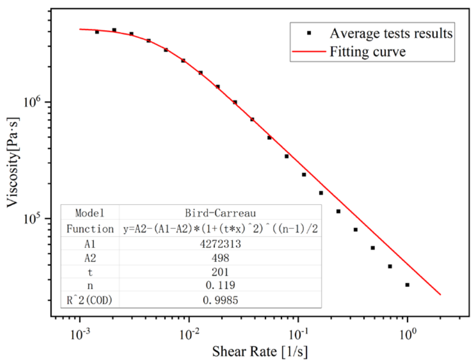

Figure 2: Flow curve of propellant material (from preference [9])

ISSN 2616-5767 Vol.7, Issue 3: 7-11, DOI: 10.25236/AJETS.2024.070302

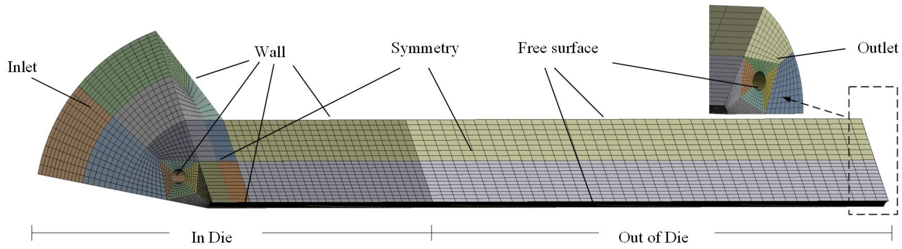

Figure 3: Mesh model and boundary sets.

Table 1: Model structural parameters.

Inlet radius R/mm	Contraction part length L_1/mm	Forming part length L_2/mm	Free part length L_3/mm	Inner hole radius r_0/mm	Forming part radius r_1/mm	Hole distance r_2/mm
3.75	2.5	12	30	0.15	1.875	1

Table 2: Parameters of Bird-Carreau model (data from preference [9]).

μ_0 /Pa·s	μ_∞ /Pa·s	λ /s	n
4254748.2	499.7	193.2	0.119

3. Dynamics simulation and analysis of forming process

3.1. Boundary conditions and solution setup

The boundary conditions for the dynamic simulation are illustrated in Figure 3. The inlet boundary is a volume flow inlet with $Q_{in} = 4 \times 10^{-7}\ m^3 \cdot s^{-1}$. The outlet boundary has zero normal and tangential forces ($f_n = f_s = 0$), while the wall boundary is a no-slip boundary with zero normal and tangential velocities ($v_n = v_s = 0$). The symmetry boundary is set with zero tangential force ($f_s = 0$) and zero normal velocity ($u_n = 0$). For the free surface boundary, the normal force, tangential force, and normal velocity are all set to zero ($f_n = f_s = 0,\ v_n = 0$). The dynamic model of the forming process was solved using the finite element software ANSYS PolyFlow. Mini-element velocity elements and Linear pressure elements were used for numerical integration. The Mini-element elements offer higher accuracy, but its computational cost is lower than quadratic elements and address incompressibility issues (LBB criterion). Optimesh-3D mesh remeshing technology was employed to update the mesh in the free surface region. Picard iteration and Evolution techniques were utilized to solve the strong nonlinear problem arising from the exponential term in the viscosity equation.

3.2. Dynamics analysis of forming process

The velocity distribution, pressure distribution, and shear rate distribution of the propellant material inside the die during the forming process of the 7-hole propellant are illustrated in Figure 4-6. Figure 7 shows the average velocity, pressure, and shear rate distributions along the forming direction.

Figure 4 displays the velocity distribution, revealing that the material in forming part has the highest flow velocity and maintains a relatively stable flow. In the contraction part, there is a significant velocity gradient, with the outer velocity higher than the inner velocity at the inlet. Due to the assumption of no-slip boundary conditions on the walls and the shear-thinning property of propellant material, there is a high velocity gradient near the walls, resulting in a velocity distribution pattern with high velocities in the middle and lower velocities on the sides. The velocity distribution curve in Figure 7 indicates that the increasing rate of velocity is on the rise inside the contraction part, reaching a peak at the junction of the contraction and forming sections, and then remains relatively constant with a slight decrease at the outlet.

Figure 5 illustrates the pressure distribution, showing a gradual decrease in pressure of the propellant from the inlet to the outlet. Within the contraction part, the outer pressure is higher than the inner pressure, with the maximum pressure occurring at the outer edge of the contraction part. In the forming part, the pressure gradient is relatively uniform, ensuring stable formation of the propellant. The pressure curve in Figure 7 reveals that the decrease rate of pressure in the contraction part is lower than that in the forming part, while the pressure decrease rate in the forming part remains relatively constant. Figure 6 displays the shear rate distribution of the propellant material inside the die, showing that the shear rate is

ISSN 2616-5767 Vol.7, Issue 3: 7-11, DOI: 10.25236/AJETS.2024.070302

highest near the walls, where significant friction effects are observed. From the shear rate curve in Figure 7, it can be observed that the shear rate is relatively low near the inlet, increases rapidly in the contraction part, remains stable in the forming part, and decreases at the outlet.

Figures 4-7 demonstrate that the propellant material exhibits a stable flow distribution in the forming part, which is beneficial for the formation of the 7-hole propellant.

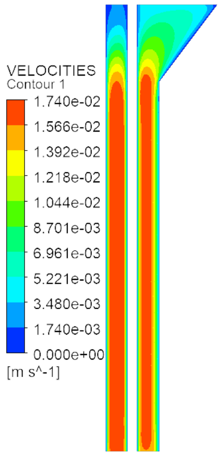

Figure 4: Velocity distribution.

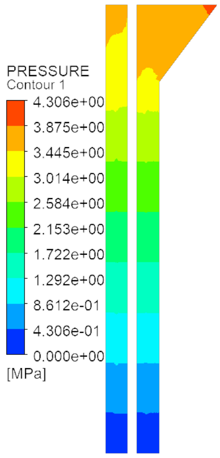

Figure 5: Pressure distribution.

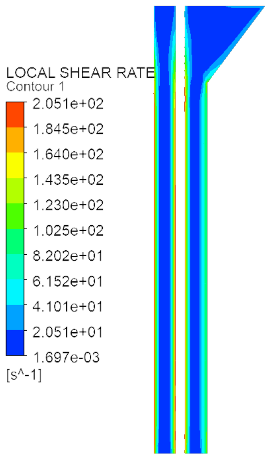

Figure 6: Shear Rate distribution.

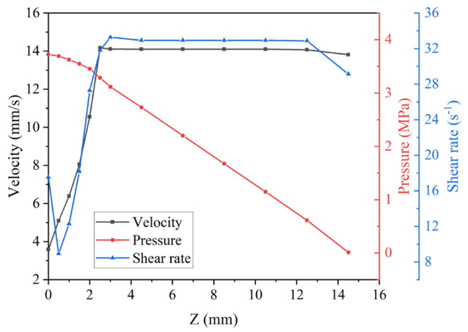

Figure 7: This caption has more than one line so it has to be set to justify.

4. Conclusions

This study conducts a dynamics simulation on the forming process of a 7-hole single-base propellant using finite element method, obtaining insights into the flow behavior of the propellant in the 7-hole forming die. The evaluation of the propellant forming quality is based on deformation rate, surface quality, and density consistency. This study provides valuable insights for optimizing the forming process of 7-hole single-base propellants.

References

[1] Martínez-Pastor J, Franco P, Moratilla D, and Lopez-Garcia P J, Optimization of Forming Processes for Gelled Propellant Manufacturing, in Modeling and Simulation in Industrial Engineering [M], M. Ram and J.P. Davim, Editors. 2018, Springer International Publishing: Cham. 1-28.

[2] Zhang D and He W, Numerical Simulation of 7-Hole Nitroguanidine-based Gun Propellant in Extrusion Forming Process[J]. Chinese Journal of Explosive & Propellants, 2015. 38(1): 82-86.

[3] Liu J, Xie Z, Wang Q, Wang Y, Chen S, and Xu C, Simulation and Experimental Verification of Flow Field of Single Screw Extrusion Mold Used in Three-Based Gun Propellant[J]. Explosive Materials, 2022. 51(01): 1-8.

[4] Zhu C, Nan F, He W, and Shen W, Numerical Simulation of Nitroguanidine Gun Propellant in Channel Considering Wall Slip Correction[J]. Chinese Journal of Energetic Materials, 2018. 26(3).

[5] Ji D, Liu Z, Liao X, Lv S, and Wang Z, Numerical simulation of Extrusion Process and Die Optimization for 19-Hole Propellant[J]. Chinese Journal of Energetic Materials, 2016. 24(11): 1114-1120.

[6] Ji D, Liu Z, Yang L, Liao X, and Wang Z, Simulation of Die Swell and Flow Uniformity of Gun Propellant Dough and Application in Die Design[J]. Chinese Journal of Explosives & Propellants, 2017. 40(4): 97-101.

[7] Lv S, Ji D, Liao X, and Wang Z, Design on Die of One-hole Propellant Based on Its Expansion and Flow Uniformity[J]. Journal of Ballistics, 2017. 29(1): 57-61.

[8] Chang F, Zhu C, Nan F, and He W, Effect of the Mold Inner Flow Channel Structure on the Forming Process of Nitroguanidine Gun Propellant[J]. Chinese Journal of Energetic Materials, 2018. 26(2): 130-137.

[9] Zou J, Rong B, Liu Y, Rui X, and Wang G, Dynamics simulation and product quality consistency optimization of energetic material extrusion process[J]. The International Journal of Advanced Manufacturing Technology, 2024. 131(3): 1497-1514.

[10] Zou J, Rong B and Rui X, Numerical simulation of the extrusion forming dynamic process of polymer material[C]. in 1st International Conference on Mechanical System Dynamics (ICMSD 2022). 2022.

[11] Oyinloye T M and Yoon W B, Application of Computational Fluid Dynamics (CFD) Simulation for the Effective Design of Food 3D Printing (A Review)[J]. Processes, 2021. 9(11): 1867.

[12] Yang F, Guo C, Zhang M, Bhandari B, and Liu Y, Improving 3D printing process of lemon juice gel based on fluid flow numerical simulation[J]. LWT, 2019. 102: 89-99.

[13] Prabhakara S and Deshpande M D, The no-slip boundary condition in fluid mechanics[J]. Resonance, 2004. 9(5): 61-71.

[14] Kalaycioglu B., Dirikolu M.H., and Çelik V., An elasto-viscoplastic analysis of direct extrusion of a double base solid propellant. Advances in Engineering Software, 2010. 41(9): p. 1110-1114.