Simulation analysis of autofretted barrel strength based on ABAQUS

Yuliang Yang1, Yezun Sun2,3 and Yue Li1

1Army Engineering University Shijiazhuang Campus, Shijiazhuang 050003, China
232382 Unit of PLA, Beijing 100071, China
3E-mail: sunyixiao003@126.com

Abstract. Autofretted technology is used generally by high-pressure guns to enhance the strength of barrels. Mechanical properties of the autofretted barrel were studied based on the finite element software ABAQUS. For the open autofretted process, a simulation model of gun barrel was established and its accuracy was verified by comparing the simulation results with theoretical results. Various stress of autofretted gun in the firing process was simulated, and the best autofretted pressure was found. For the closed autofretted process, autofretted pressure was affected by the gap amount between the mold and the barrel.

1. Introduction
Autofretted technology is an effective measure to improve the strength and life of the barrel. During the manufacturing process, the high pressure is applied to the inner bore of the barrel, so part or all of the inner wall cause plastic deformation, as shown in Figure 1. When the high pressure is removed, the residual stress is generated in the inner wall, which can make the barrel to withstand higher bore pressure and improve the strength [1-2]. Autofretted methods include hydraulic autofretted method, mechanical autofretted method and explosive autofretted method [3-4]. According to the existence of a mold outside the barrel, it is divided into the open and closed autofretted process.

2. Theoretical calculation of elastic strength limit
For the open autofretted process, the gun barrel strength was usually analyzed by the third strength theory or the fourth strength theory [5-6]. Based on the third strength theory, the critical pressure $P_{13}$ when the inner surface begins to cause plastic deformation can be calculated.
\[ P_{13} = \sigma_s \frac{r_i^2 - r_1^2}{2r_1^3} \]  

(1)

Where, \( \sigma_s \) was the yield stress, \( r_i \) was the inner diameter, \( r_2 \) was the outer diameter. On the fully plastic state, the critical pressure \( P'_{13} \) can be calculated.

\[ P'_{13} = \sigma_s \ln \frac{r_2}{r_1} \]  

(2)

Similarly, the critical pressure can be calculated by the fourth strength theory.

\[ P_{14} = \sigma_s \frac{r_i^2 - r_1^2}{\sqrt{3r_2^4 + r_1^4}}, \quad P'_{14} = 1.08\sigma_s \ln \frac{r_2}{r_1} \]  

(3)

3. Finite element simulation of open autofrettaged process

3.1. Finite element modeling

For the strength analysis of mechanical components, finite element calculation is an effective method [7-8]. Based on the finite element software ABAQUS, the simulation model of a certain type of gun barrel was established, according to its structure size and material parameters, as shown in Figure 2. The simulation model contained 5400 elements, with the element size of 1mm. The main parameters were shown in Table 1, of which \( \nu \) was the poisson’s ratio, \( E \) was the elastic modulus.

![Figure 2. Finite element simulation model of barrel (part 1/4).](image)

### Table 1. Main parameters of barrel.

| Parameters | \( \nu \) | \( E \) | \( \sigma_s \) | \( r_1 \) | \( r_2 \) |
|------------|---------|------|------------|------|------|
| Values     | 0.27    | 203GPa | 1041MPa    | 61mm | 110mm |

3.2. Simulation model verification

The critical stress values can be obtained respectively from the fourth strength theory and the finite element model, as shown in Table 2, Figure 3 and Figure 4. The accuracy of the simulation model can be verified by comparing simulation results with theoretical results.

### Table 2. Critical stress values.

| Parameters     | \( P_{14} \) | \( P'_{14} \) |
|----------------|-------------|-------------|
| Theoretical value | 410 MPa     | 663 MPa     |
| Simulation value   | 416MPa      | 678 MPa     |
| Relative error      | 1.46%       | 2.26%       |
Figure 3. Stress contour (p=417MPa).

Figure 4. Stress contour (p=678MPa).

3.3. Determination of the best autofretted pressure

The application of autofretted technology effectively improves the elastic strength limit and fatigue life of the barrel. But the autofretted pressure cannot be too large or too small. If it is too small, the effect it plays is small. If it is too large, it will damage the barrel, cause cracks and other brittle fractures. Therefore, the best autofretted pressure need to be found. On the best autofretted pressure, the maximum equivalent stresses in the normal and working conditions must be at a minimum state [9, 10]. The shooting pressure of the barrel is 300MPa. Based on the simulation model, the maximum residual stress $\sigma'_E$ and working stress $\sigma_E$ of the barrel were analyzed under different autofretted pressure $p$, respectively shown in Table 3 and Figure 5.

It can be seen from Figure 5 and Table 3, as the autofretted pressure increased, the maximum residual stress gradually increased. The change law of the maximum working stress can be divided into two stages. In the first stage with the autofretted pressure from 400 MPa to 520MPa, the maximum working stress decreased rapidly, because the residual stress offeseted some part of working...
stress. In the second stage with the autofretted pressure more than 520MPa, the maximum working stress changed slowly and tends to be stable. Therefore, the best autofretted stress was 520MPa.

Table 3. The maximum residual stress and working stress.

| $p$ /MPa | $\sigma'_y$ /MPa | $\sigma_y$ /MPa | $p$ /MPa | $\sigma'_y$ /MPa | $\sigma_y$ /MPa |
|---------|-----------------|-----------------|---------|-----------------|-----------------|
| 0       | 0               | 750.2           | 560     | 391.8           | 595.7           |
| 420     | 9.87            | 740.9           | 580     | 448.4           | 592.1           |
| 460     | 117.3           | 675.5           | 600     | 505.0           | 593.0           |
| 500     | 226.1           | 630.6           | 620     | 562.1           | 598.4           |
| 520     | 281.0           | 614.9           | 640     | 619.5           | 611.7           |
| 540     | 336.3           | 603.5           | 660     | 677.6           | 635.2           |

Figure 5. The maximum residual stress and working stress curves.

Figure 6. Simulation model of closed autofretted barrel.

4. Finite element simulation of closed autofretted barrel

During the closed autofretted process, there was a mold outside the barrel. The mold used the better alloy steel, with the bigger yield stress and elastic modulus. The inner diameter and outer diameter of the mold were respectively 110mm and 150mm. By controlling the gap amount between the mold and the barrel, the plastic deformation of the barrel was precisely controlled. The gap amount affected the autofretted pressure values. Based on the simulation model, the autofretted pressure when the inner
surface of the barrel caused plastic deformation corresponding to different gap amount was analyzed, as shown in Figure 6.

![Figure 6](image6)

**Figure 6.** Surface deformation map of barrel.

It can be seen from Figure 7, when the gap amount was 0, the mold and the barrel fitted together, which greatly limited the external deformation of the barrel, so the autofretted pressure was the greatest. As the gap increased, the autofretted pressure gradually decreased. When the gap is greater than 0.2mm, the autofretted pressure was basically the same as the open autofretted process.

![Figure 7](image7)

**Figure 7.** Autofretted pressure curve.

5. Conclusions

1. Mechanical properties of the autofretted barrel were studied based on the finite element software ABAQUS, and the accuracy of the simulation model was verified by comparing the theoretical value with the simulation value.
2. For the open autofretted process, in order to ensure the normal and working stress strength of the barrel, the best autofretted pressure of 520MPa was obtained.
3. For the closed autofretted process, when the gap amount was very small, the the autofretted pressure was greater than that of the open autofretted process. When the gap was more than 0.2mm, the autofretted pressure was basically the same as the open autofretted process.

References

[1] Du Zhonghua, Wu Dalin and Liu Haiping 2019 Numerical simulation of self-tightening tube strength based on different strength theories[J]. Mechanical Engineer (2) 74-76
[2] Chang Liezhen, Pan Yutian, Ma Xinmou, et al. 2013 Numerical simulation on mechanical property of hydraulic autofrettage gun tube[J]. Journal of North University of China (Natural Science Edition) (2) 124-127
[3] Zhang Xiangyan, Zheng Jianguo and Yang Junrong 2005 Artillery design theory[M]. Beijing: Beijing Institute of Technology Press
[4] Zheng Zuhua 2013 Strength analysis of large caliber autofretted barrel based on the finite element method[D]. Hefei: Hefei University of Technology
[5] Liu Dawei 2018 Research on the Expansion of Basic Strength Theory[J]. Journal of Lanzhou University of Arts and Science (Natural Sciences) 32(05) 41-45
[6] Sun Songsong, Wan Maosong, Xu Xiaomei, et al. 2019 Comparable Application of Different Strength Criterions in Crankshaft Fatigue Researches[J]. China Mechanical Engineering 30(23) 2784-2789
[7] Namik Kilic, Bulent Ekici and Selim Hartomacioglu 2015 Determination of penetration depth at high velocity impact using finite element method and artificial neural network tools[J]. Defence Technology 11(02) 110-122
[8] Wang Hongyan, Hong Huangjie, Li Jianyang and Rui Qiang 2013 Study on Multi-objective
Optimization of Airbag Landing Attenuation System for Heavy Airdrop[J]. *Defence Technology* 9(04) 237-241

[9] Liang Fei 2012 Parameters design and software platform development of gun autofrettage process[D]. Nanjing: Nanjing University of Science and Technology

[10] Zhou Minhua, Li Xiaoqian, Liu Rongguang, et al. 2008 The finite element analysis of the best autofrettaged pressure of thick-walled cylinder[J]. *Modern Manufacturing Engineering* (8) 111-114