Simulation analysis of residual stress of autofrettaged barrel under multi-field coupling loads

X K Gao\textsuperscript{1,*}, Q He\textsuperscript{1}, P K Liu\textsuperscript{1}, X J Shao\textsuperscript{1} and Z S Wang\textsuperscript{1}.

\textsuperscript{1}Northwest Institute of Mechanical & Electrical Engineering, Xianyang 712099, Shaanxi China.

Email: xiaokgao@qq.com.

Abstract. High-pressure guns repeatedly withstand transient high pressures and high temperatures, which have a great influence on the residual stress of the barrel. In order to study the stress distribution of autofrettaged barrel under multi-field coupling during launch, the mechanical autofrettage gun barrel and finishing process of the barrel was simulated by ANSYS finite element software, in which the finite element model considering the initial residual stress of the autofrettaged barrel was established, and the dynamic and static continuous process simulation of the barrel was carried out. On the basis of obtaining the residual stress distribution, an analytical model under the coupling of transient pressure field and temperature field is established. The APDL language programming is used to calculate the time and space distribution of the stress of the key parts of the barrel. A phenomenon is found that the equivalent stress on the outer surface of the barrel increases sharply with the increase of the pressure, and then rises to the highest point with the temperature of the barrel. After the fire process, the equivalent stress slowly recovers with the decrease of the temperature. The law of external surface stress rise in the fire period is a step process. It provides a theoretical basis for studying the residual stress release law the safety design of barrel.

1. Introduction
The new generation of large caliber and high-performance tank gun requires that the barrel can meet the requirements of high initial speed, high firing speed, high bore pressure, high life and higher temperature. Autofrettage technology is a kind of technology which can improve the bearing capacity of the barrel by producing favorable residual stress in the barrel without changing the barrel material. It has been widely used in the world in recent decades to improve the barrel performance and extend the service life [1].

The commonly used technology of self-tightening barrel includes mechanical method, hydraulic method and explosion method [2]. There are distinctions in the operation process of different self-tightening technology, but the basic principles are the same. Before the final finish machining of gun barrel, the pressure beyond the initial yield strength of the barrel is applied to the barrel bore roughcast. The inner diameter of the barrel is enlarged, the inner wall is compact, and the uneven plastic deformation is produced along the wall thickness from inside to outside. When the internal pressure is removed, the relative elastic recovery of each layer is smaller than that of the adjacent outer layer, the inner layer will prevent the elastic recovery of the outer layer. This kind of constraint eventually causes the circumferential residual stress is compression in the inner layer and tension in the outer layer along the wall thickness of the barrel [3]. When the gun fires, the compressive residual stress in the inner wall...
and the tensile stress produced by the bore pressure are superposed, which reduces the actual stress level of the barrel, thus improving the elastic limit pressure and fatigue life of the barrel [3].

Compared with Europe, America, Russia and other military powers, the research on self-tightening barrel technology started late in China. Since the 1970s, the research on self-tightening management theory and technology has been carried out around the subjects of high bore pressure gun barrel mechanical self-tightening technology and gun barrel fatigue life. However, there are still many problems in the design of self-tightening barrel, such as the residual stress release law of the whole life cycle, and the safety theory of self-tightening barrel, which need to be further studied.

The autofrettage tube is mainly subjected to high pressure and high temperature load in the bore during the shooting process. Some studies have shown that under the action of thermal stress caused by the temperature difference between the inner and outer walls and the high bore pressure, the inner wall produces reverse yield (compression yield), which reduces the residual stress and leads to the relaxation of the residual stress. In addition to the effects of pressure shocks in the bore, high temperature and thermal stress are also the main factors that cause the residual stress release in the self-tightening tube. Hu Z J [4] analyzed the stress variation of the barrel during the launch of large-caliber artillery through thermoelastic coupling. Xu Y D and Qian L F [5] studied the transient thermal structure coupling of composite barrels by theoretical and modeling analysis according to the structural characteristics of composite barrel. For the fast-firing artillery, Li Q [6] considered the effects of gunpowder gas and thermal stress, analyzed the change law of residual stress for self-tightening barrel during the bursting process.

In order to study the change of residual stress in the shooting process, it is necessary to model the whole process accurately and consider the coupling effect of bore pressure and temperature gradient. In this paper, the process of mechanical self-tightening and finishing of the barrel was simulated by ANSYS software, and a finite element analysis model considering the initial residual stress of autofrettaged barrel was established. The static and dynamic continuous process simulation of the barrel was carried out to study the residual stress distribution of the barrel after mechanical self-tightening and surface finishing. The stress variation in key parts of barrel was analyzed under the coupling of transient pressure and temperature field. This paper provides a theoretical basis for the safety design of barrel.

2. Basic Equations of Thermal Structure Coupling

When the gun is launched, the barrel is impacted by the pressure load of gunpowder and thermal shock. According to the relationship between thermodynamics and heat transfer [5], the basic equation of heat conduction can be obtained shown in equation (1)

\[
\frac{\partial}{\partial t} (k \frac{\partial T}{\partial t}) + \frac{\partial}{\partial x} (k \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y} (k \frac{\partial T}{\partial y}) + \frac{\partial}{\partial z} (k \frac{\partial T}{\partial z}) + \rho C \frac{\partial T}{\partial t} = \rho C \frac{\partial T}{\partial t}
\]

(1)

Where, \( Q \) is the heat absorbed in unit time; \( T_0 \) is the initial temperature of object; \( e = \varepsilon_x + \varepsilon_y + \varepsilon_z \) is the total strain; \( \beta \) is the thermal stress coefficient; \( k \) is the heat transfer coefficient; \( c \) is the specific heat capacity; and \( \rho \) is density.

Based on the equations of motion, geometry and physics, the basic equations of thermoelastic theoretical displacement method were established as in equation (2)
3. Residual stress analysis model

3.1. Geometric model

The barrel model is shown in figure 1. From top to bottom, it is the blank barrel, tungsten carbide self-tightening punch bullet and finished barrel.

The birth and death element technology of ANSYS was used in the simulation of barrel finishing process. Since elements can only be created in the preprocessor for ANSYS, all possible elements must be created in the preprocessor at one time, including the killed (or activated) cells in each load step.

The overall geometric model is shown in figure 2.

\[
\begin{align*}
(\lambda + G) \frac{\partial e}{\partial x} + G \nabla^2 u - \beta \frac{\partial T}{\partial x} + X &= \rho \frac{\partial^2 u}{\partial t^2} \\
(\lambda + G) \frac{\partial e}{\partial y} + G \nabla^2 v - \beta \frac{\partial T}{\partial y} + Y &= \rho \frac{\partial^2 v}{\partial t^2} \\
(\lambda + G) \frac{\partial e}{\partial z} + G \nabla^2 w - \beta \frac{\partial T}{\partial z} + Z &= \rho \frac{\partial^2 w}{\partial t^2}
\end{align*}
\]

3.2. Mesh generation

The regular quadrilateral element is used to the reasonably partition geometric model. The element size is about 3mm. The whole model includes 36817 nodes and 40490 axisymmetric plane elements.

3.3. Boundary conditions and loads

Because the axisymmetric model was adopted, the axial freedom of top and bottom end lines of the model were constrained, and the self-tightening forced displacement is applied to the bottom end line of the punch. The boundary conditions are shown in figure 3.

Figure 1. Blank barrel, punching bullet and finishing barrel.

Figure 2. Geometric model.

Figure 3. Boundary condition.

Figure 4. Press versus time curve.
The relationship between time $t$, bore pressure $P$ and projectile travel $L$ obtained from interior ballistic simulation are shown in figure 4 and figure 5. Due to the large amount of data, the changes of temperature field with time and projectile travel were omitted here. Figure 6 shows the temperature time history curve at different positions of the inner surface of the barrel from the tail end.

Figure 5. Boundary condition.

Figure 6. Temperature time history curve at different positions of the inner surface of the barrel from the tail end.

4. Simulation process
The autofrettage barrel residual stress analysis process includes three stages. (1) Mechanical self-tightening process. (2) The finishing process of inner and outer surface of blank barrel and punching bullet. (3) coupling effect of bore pressure and temperature field during launching process.

The first two steps are static analysis. The punch mechanical self-tightening is similar to the general static simulation process, but the finishing process requires ANSYS element birth and death technology. In the element birth and death technology, the killed element is simply a multiplication of the element stiffness matrix by a small factor, and it is not really deleted from the model. That is, the mass and energy of the killed element do not participate in the solution, and the strain of the element is always 0. Since elements can only be created in the preprocessor, all possible elements must be created at one time. The third step is transient analysis. Based on the analysis of the first two steps, the temperature field and bore pressure that change with time and position on the barrel continue to be applied. The simulation process was performed continuously using ANSYS-APDL programming. The simulation flow is shown in figure 7.
5. Simulation results

Based on the analysis of the mechanical self-tightening process and the finishing process of the blank barrel, the transient analysis type is converted by command control. The coupling effect of bore pressure and temperature field, which changes with time and position at the same time, is continuously applied. The transient process of barrel launching is simulated by setting the ambient temperature to 13°C.

The launching time of tank gun is very short, about 8.5ms, while the heat transfer and temperature rise along the wall thickness are relatively slow. In order to fully reflect the influence of temperature on the deformation and stress response of the barrel, the gun launching process was simulated for one minute after launching.

Figure 8 to figure 11 shows the overall response law of radial and axial deformation of the inner and outer surface of the maximum press point. It can be seen from the figures that:

1) The radial deformation of the inner and outer surfaces is the same, and the deformation of the inner surface is larger than that of the outer surface.

2) In the stage of mechanical self-tightening, the radial deformation increases sharply with the extrusion of punch, and the larger plastic deformation occurs with the recovery of elastic deformation after the punch leaves. The radial deformation of internal and outside surface is 0.673mm and 0.324mm respectively. The radial deformation of the internal surface is slightly retracted during processing while
the outside surface and the end surface are only slightly enlarged. The radial deformation of the inner and outer surface of the finished barrel is 0.638mm and 0.311mm, which shows that the plastic deformation of this part is basically the result of self-tightening process.

(3) The axial deformation of the inner and outer surface of the finished barrel is 0.192mm and -0.138mm respectively, which indicates that the cross section of the part has dislocation phenomenon during the processing. The expansion of barrel under the action of bore pressure makes the axial deformation of this part contract first and then extend.

(4) In the launching process, the barrel diameter increases rapidly with the instantaneous rise of the barrel pressure, fell back rapidly with the disappearance of the barrel pressure, then increases with the rise of the barrel temperature, and finally recovers slowly the decrease of the temperature. The maximum radial deformation of internal diameter and external diameter in bore is 0.212mm and 0.141mm respectively.

(5) In the fire process, with the coupling of bore pressure and temperature field, the radial deformation expands and the axial deformation contracts. The inner surface deformation of barrel is greater than the outer surface.

(6) At the time of one second after launch, the temperature of the barrel is still high (the inner wall is about 150℃), the axial deformation of the barrel has not been fully recovered, and the inner and outer walls are in the tensile state. The radial deformation of the inner wall also lags behind that of the outer wall.

Figure 8. Radial deformation of the maximum press point.

Figure 9. Radial deformation of the maximum press point in the fire process.

Figure 10. Axial deformation of the maximum press point.

Figure 11. Axial deformation of the maximum press point in the fire process.

Figure 12 to figure 15 shows the response law of internal surface stress and external surface stress at the maximum press position. It can be seen from the figures that:
(1) The large residual stress produced in the autofrettage stage is basically maintained when the barrel finish machining is finished, which indicates that the plastic stress (mainly radial stress) in this part is produced in the autofrettage process.

(2) In the process of gun launching, the equivalent stress on the internal surface decreases sharply with the instantaneous increase of bore pressure, and then decreases to the lowest point with the increase of barrel temperature. After that, it recovered slowly with the decrease of temperature. The internal surface equivalent stress is less than the initial residual stress.

(3) In the process of fire, there are great stress fluctuations in the circumferential, axial and radial directions of the internal surface.

(4) From autofrettage and finish machining to transient launching, the circumferential and axial stress of the external surface is always tensile stress. When the gun is launched, the circumferential stress of the external surface fluctuates in a large range, the axial stress is small, and the radial stress changes in a small range.

(5) In the process of gun launching, the equivalent stress on the external surface increases rapidly with the instantaneous increase of the bore pressure, and falls rapidly with the disappearance of the bore pressure. In the process of fire, the stress on external surface rises step by step.

(6) One minute after launching, the equivalent stress of internal surface and external surface decreased by 379MPa and 174MPa respectively, indicating that the release of residual stress in internal surface was obvious at the maximum press position and relatively small at external surface.

\[\text{Figure 12. Internal surface stress response of the maximum press position.}\]

\[\text{Figure 13. Internal surface stress response of the maximum press position in the fire process.}\]

\[\text{Figure 14. External surface stress response of the maximum press position.}\]

\[\text{Figure 15. External surface stress response of the maximum press position in the fire process.}\]

Variation of residual stress in launch process.

5.1. Quantification of residual stress loss
In the process of fire, the residual stress in the autofrettage barrel decreases continuously. The reduced value is the initial residual stress of barrel minus the residual stress after launching. Table 1 shows the test data of the residual stress loss on the internal surface of the self-tightening barrel launched by four different projectiles.

Table 1. Residual stress loss on internal surface of self-tightening barrel.

| Number | Projectile number | $\sigma_{\theta r}$/MPa | $\sigma_{\theta i}$/MPa | $\sigma_w$%
|--------|------------------|-------------------------|-------------------------|-----|
| 0081   | 203              | -594.5                  | -429.5                  | 27.8 |
| 0231   | 205              | -607.2                  | -440.4                  | 27.5 |
| 0156   | 297              | -596.8                  | -390.7                  | 34.5 |
| 0129   | 355              | -605.1                  | -395.7                  | 34.6 |
| 0016   | 460              | -589.5                  | -368.5                  | 37.5 |

$\sigma_{\theta r}$ is the residual stress on the internal surface of the barrel, $\sigma_{\theta i}$ is the initial residual stress on the internal surface of the barrel, and $\sigma_w$ is the percentage of residual stress attenuation, $\sigma_w = \frac{\sigma_{\theta i} - \sigma_{\theta r}}{\sigma_{\theta i}} \times \%$.

According to the data in table 1, the relationship between the attenuation of the tangential residual stress on the internal surface and projectile number is as follows:

$$\sigma_w = a_0 + a_1e^{(n/T)} \quad (3)$$

Where $a_0 = 37.5$, $a_1 = -37.5$, $T = 141.6$, $n$ is the number of projectiles.

Equation (3) is the relationship between the residual stress of self-tightening barrel during launching and the number of projectiles. By using the formula, as long as the number of shots is known, the loss of residual stress in the autofrettage barrel can be predicted. The relationship between the percentage of residual stress attenuation and the number of projectiles is shown in figure 16.

5.2. Analysis of the release law of residual stress

From formula 3 and figure 16, it can be seen that the change of residual stress in the self-tightening barrel with the number of projectiles basically conforms to the exponential law. When the number of shots exceeds 400, the change of residual stress tends to be gentle. The variation of residual stress from 0 to 400 projectiles is large, and the average reduction of initial residual stress per 100 projectiles is about 8.5%. However, the average reduction of initial residual stress per 100 projectiles is about 8.5% from 400 to 1000 projectiles.

In the course of service, the residual stress of autofrettage barrel is released with the process of launching. When the number of shots reaches a certain number, the change of residual stress tends to be stable. However, the magnitude and distribution of residual stress are very different from the initial
residual stress, especially on the internal surface. The comparison curve of initial residual stress and final residual stress of No.0016 barrel sample is shown in figure 17, and the rest of barrels are similar to it.

Figure 17. Comparison curve of No.0016 residual stress and initial residual stress.

5.3. The main factors affecting the release of residual stress
During the launching process of self-tightening tube, the inner bore has the basic characteristics of high pressure and high temperature. Generally, the chamber pressure is above 500MPa. The firing frequency is about 10 per minute, and the thickness of the barrel in the highest chamber pressure area is generally greater than 50mm. This makes the internal surface of the gun at higher temperature and the external surface at lower temperature in the early stage of launching. The superposition of residual stress and thermal stress which caused by internal and external temperature difference makes the internal surface of the barrel compression yield, resulting in the decrease of residual stress. The extent of reduction increases with the increase of thermal gradient and self-tightness in barrel. With the continuous firing, the temperature in the barrel tends to balance gradually, and the decrease of residual stress becomes gentle. But in the normal service process, this kind of large caliber gun does not shoot hundreds of times continuously like the small caliber anti-aircraft gun. Therefore, the actual total number of shots is the accumulation of the number of staged shots. A large number of studies show that high temperature and thermal stress are the main factors that cause the release of residual stress in self-tightening barrel, such as ‘the reduction of residual stress caused by stabilization treatment’, ‘thermal relaxation in self-tightening cylinder’ [4], ‘residual stress in self-tightening thick-walled tube’ [5] and so on. The firing pressure only works in combination with thermal stress, because under the firing pressure, the high temperature will accelerate the reduction of the yield strength of the barrel, and make the residual stress release more quickly.

6. Summary and conclusion
In this paper, a precise residual stress analysis model of autofrettage barrel is established, considering the process of mechanical self-tightening, barrel surface finishing and gun launching. A simulation program for residual stress analysis of autofrettage barrel is developed by ANSYS software, which realizes the static and dynamic continuous process simulation of autofrettage tube. The analysis process includes the mechanical self-tightening of blank barrel, machining of internal surface and external surface, and gun launching under the coupling effect of the chamber pressure and temperature field of finished barrel.

This paper focuses on the analysis of plastic deformation and residual stress variation along the radial direction of the barrel in each stage, and studies the temperature rise process of critical position. Combined with the analysis and fitting of test data, the basic conclusions are as follows:

(1) After mechanical self-tightening and finish machining, the barrel has a large residual stress (mainly circumferential stress), which can offset most of the tensile stress produced by gun launching, and achieve the purpose of reducing the actual stress level of barrel.
(2) The residual stress in the autofrettage tube decreases in launching process, and the variation of the residual stress basically shows an exponential law with the firing time.

(3) The variation of residual stress release is larger when the number of shots is less than 400, while it tends to be gentle when the number of shots is more than 400.

(4) The main factors affecting the release of residual stress is high temperature in bore and thermal stress caused by the temperature gradient during launching. The release of residual stress is enhanced by the simultaneous existence of bore pressure, high temperature and thermal stress.

The calculation method and simulation program in this paper can provide theoretical and methodological support for the strength design, life prediction of autofrettaged barrel and the improvement of gun lunch safety.

References
[1] Zeng Z Y and Zhang J L 2004 Strength design theory on gun tube (Beijing: National Defense Industry Press) 160-4
[2] Cai H N , Zhang Y C , Xu B Y and Huang S X 1997 Technique of Autofrettage for gun tube (Beijing: Ordnance Industry Press) 135-52
[3] Li K W, Zeng Z Y, Ning B F, Liu P K and Gao X K 2012 Acta Armamentarii 33 (11) 1298-302
[4] Hu Z J 2007 Thermal-elastic coupling analysis of barrel during gun launch(Nanjing: Nanjing University of Science and Technology) 43-5
[5] Xu Y D, Qian L F and Shi X D 2007 J. Nanjing University of Science and Technology 31(2) 350-3
[6] Li Q, Li P H, Zhao J G and Ru Z Y 2011 Explosion and Shock Waves 31(06) 635-40