Research on the stress and strain state of gun barrel during rapid firing

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ABSTRACT

This study investigates the stress–strain behavior of a gun barrel under rapid firing conditions using the finite element method implemented in ANSYS Workbench. The numerical model considers the coupled effects of internal pressure and transient thermal loading to simulate the thermo-mechanical response of the barrel during continuous firing. The results, presented through stress–strain curves, contour plots, and time-dependent visualizations, reveal the evolution of stress concentration, plastic deformation, and material degradation in the barrel structure. The analysis demonstrates that repeated thermal and pressure cycles significantly affect the strength, fatigue resistance, and service life of the barrel. The findings provide a scientific foundation and computational reference for design optimization, material selection, manufacturing processes, and strength verification of modern artillery barrels, contributing to enhanced reliability and durability in high-rate firing applications.

Keywords: Gun barrel; Stress-strain; Rapid firing; ANSYS.

1. INTRODUCTION

The gun barrel is a critically important component of an artillery system; its operation involves highly complex phenomena occurring over short time intervals and is subjected to intense internal pressure and elevated temperatures. These severe operating conditions induce significant thermal and mechanical stresses and strains, which can result in deformation, wear, and material degradation of the barrel, thereby adversely affecting its service life, operational reliability, and firing accuracy [1, 2].

Previous studies on the stress–strain behavior of gun barrels have mainly focused on the thermal and pressure effects acting on the barrel wall during single-shot firing, while the influence of rapid firing has received comparatively little attention [3, 4]. In practice, however, modern artillery systems often operate under rapid firing conditions, where both the internal pressure and temperature within the barrel rise sharply in a very short period. These extreme and repetitive loads generate more severe and complex thermo-mechanical stresses and strains, which can lead to material degradation, plastic deformation, and local failure. The critical regions most susceptible to such damage include the chamber area, where the propellant gas pressure reaches its maximum, and the muzzle region, which experiences strong temperature gradients and high dynamic stresses [5]. Understanding these coupled effects is essential for accurately predicting barrel performance, structural integrity, and service life [6, 7]. The finite element method (FEM) is a robust numerical approach used to analyze complex engineering systems where analytical solutions are impractical. By discretizing structures into smaller elements, FEM enables accurate prediction of stress, strain, and thermal behavior under realistic loading and boundary conditions. It has become a standard tool in computational mechanics for structural and thermal simulations [8, 9].

Accordingly, this study employs the finite element method (FEM) to calculate and simulate the stress–strain state at critical regions of the gun barrel under the combined effects of propellant gas pressure and temperature during rapid (continuous) firing.

2. RESEARCH METHODS

Based on theoretical calculations of the barrel's thermo-mechanical response and the operational characteristics of the 25-mm naval anti-aircraft gun system, we performed transient thermal and transient structural analyses in ANSYS Workbench to evaluate the stress and strain states at three selected cross-sections following six consecutive firing events. The coupled simulations (Transient Thermal → Transient Structural) were used to capture the time-dependent temperature evolution and the resulting elastic–plastic deformation and stress redistribution induced by the firing sequence. Threeion of three cross-sections are: At the beginning of the rifling (denoted as DRX); at the position of maximum gas pressure (denoted as Pmax); and near the muzzle (denoted as DN). The surveyed cross-section specifications are presented in table 1.

Table 1. *Survey cross-section specifications.*

Cross-section position	DRX	Pmax	DN
Outer barrel diameter (mm)	65.58	60	36
Rifling grooves diameter (mm)	25	25	25
Rifling lands diameter (mm)	25.58	25.58	25.58
Travel time when a shot bullet is surveyed (s)	0	0.0012	0.0040
Propellant gas average temperature (K)	1274	1256	1218
Convective heat transfer coefficient inside gun barrel (W/mm^2.K)	0.0129	0.0126	0.0073

The material used for the 25mm gun barrel, which serves as input data for thermal field, stress, and strain analysis, is steel 38XH3MΦA GOST 4543-16 [10, 11] with its specifications presented in table 2.

Table 2. *25 mm gun barrel material specifications.*

T - Temperature (^{o}C)	E - Elastic modulus (Pa)	α - Thermal expansion coefficient (1/K)	λ - Thermal conductivity coefficient (W/m.K)	ρ- Density (kg/m3)	C - Specific heat capacity (J/(kg.^{0}K))	υ - Poisson's ratio
20	2.14E+11	1.01E-05	48	7900	440	0.3
100	2.11 E+11	1.19E-05	46	7900	466	0.3
200	2.06 E+11	1.25E-05	42.7	7900	508	0.3
300	2.03 E+11	1.32E-05	42.3	7900	529	0.3
400	1.85 E+11	1.38E-05	38.5	7900	563	0.3
500	1.76 E+11	1.41E-05	35.6	7900	592	0.3
600	1.64 E+11	1.44E-05	31.9	7900	622	0.3
700	1.43 E+11	1.46E-05	28.8	7900	634	0.3
800	1.32 E+11	1.49E-05	26	7900	664	0.3

The following assumptions are used to create the model: The barrel is a thick cylindrical tube, considering no heat flow around it; The barrel heating is only caused by the propellant gas and the friction between the driving band and the barrel surface during firing; During the post-firing phase, the heat exchange between the working gases and the barrel wall is assumed to be zero, implying no heat transfer occurs within this period. There are no heat flows or sources within the barrel wall material; Thermal deformation and changes in barrel wall thickness due to wear during firing are neglected. With the above assumptions combined with the features of the axisymmetric problem, the gun barrel model is constructed as a 2D model of a quarter of the surveyed cross-section and meshed as shown in figure 1.

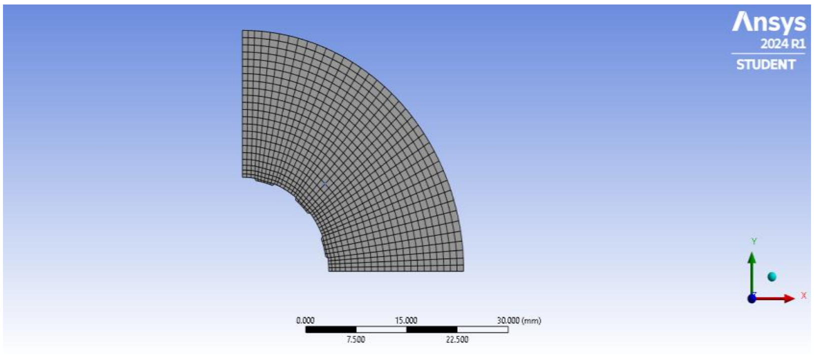


Figure 1. *Finite element model of a quarter of the surveyed cross-section.*

3. RESULTS AND DISCUSSION

3.1. Temperature field of the gun barrel when firing

After firing six consecutive rounds within 0.8 seconds, the temperature distribution within the gun barrel over time at the surveyed cross-sections is represented in the form of images and graphs, as shown in figures 2, 3, 4, and 5.

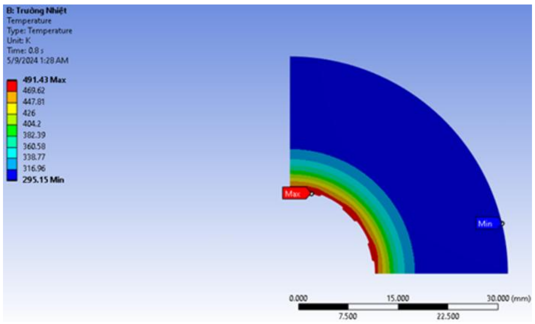


Figure 2. *Temperature distribution at DRX.*

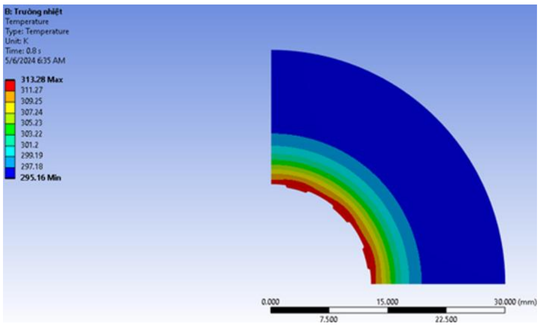


Figure 3. *Temperature distribution at Pmax.*

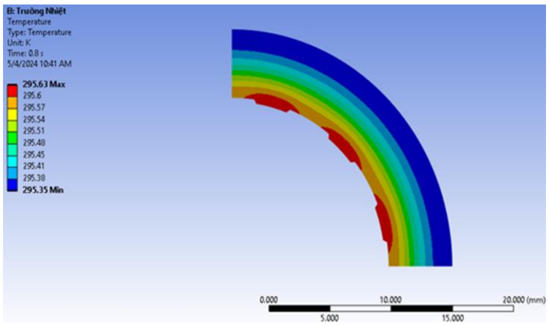


Figure 4. *Temperature distribution at DN.*

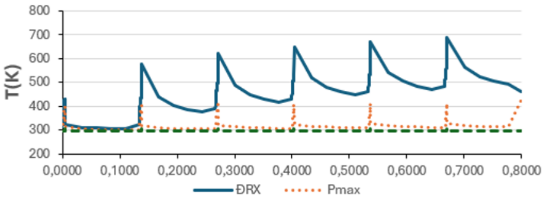


Figure 5. *Maximum temperature at 3 cross sections over time.*

At the beginning of the spiral rifling, the heating is greatest and gradually decreases toward the barrel tip. This is explained by the fact that the duration of heat exposure and the intensity of heat exchange gradually decrease toward the barrel tip. The temperature distribution in the barrel wall shows a distinct difference across the layers, as shown in the diagram (figures 2, 3, 4), with the outermost layer of the barrel having a relatively low temperature. After each shot, the barrel temperature increases (figure 5) and, to a certain extent, alters the firing parameters, affecting the accuracy of the shot. Therefore, each type of artillery gun has a specified number of shots with different barrel cooling conditions. During the thermal impact of firing, the temperature only increases in a thin layer of metal close to the inner surface of the barrel (figures 2, 3, 4). The rate of temperature change at different layers varies according to the thickness of the barrel; layers closer to the heated surface experience greater temperature changes (figures 2, 3, 4). Between shots, the process of redistributing heat from the inner surface to the outer surface of the barrel cannot be completed in time. Therefore, the closer the surveyed point is to the inner surface of the barrel, the greater the temperature fluctuation at that point. As the distance from the inner surface increases, temperature fluctuation weakens while the temperature increases monotonically. Thus, the observed trend in temperature variation analyzed using ANSYS fully aligns with the theory, and thus, the calculated results are reliable.

3.2. Stress and strain at different cross-sections

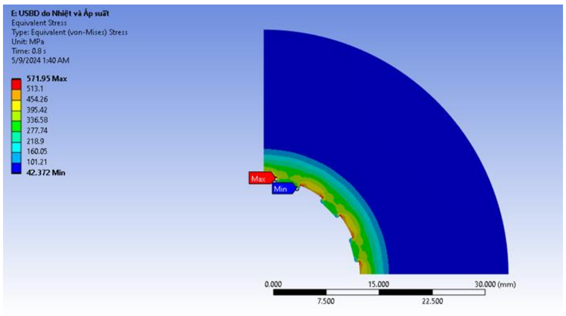


Figure 6. *Stress at cross-section DRX.*

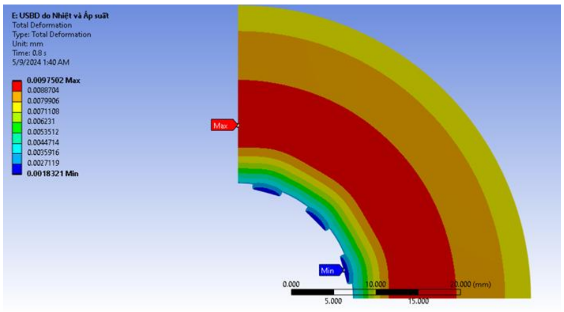


Figure 7. *Strain at cross-section DRX.*

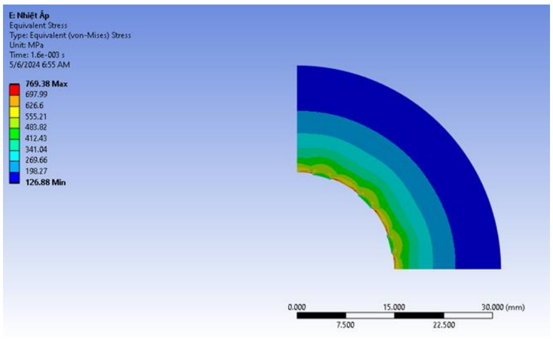


Figure 8. *Stress at cross-section Pmax.*

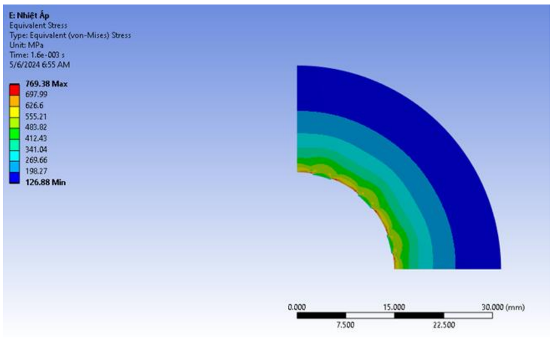


Figure 9. *Strain at cross-section Pmax.*

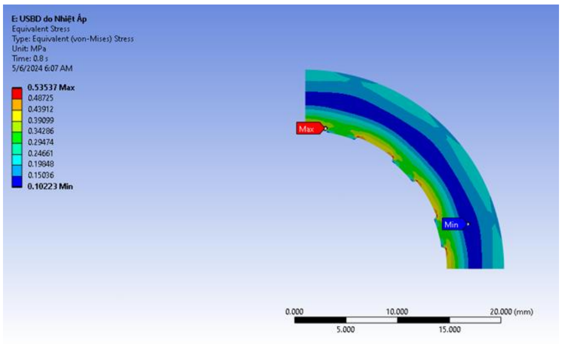


Figure 10. *Stress at cross-section DN.*

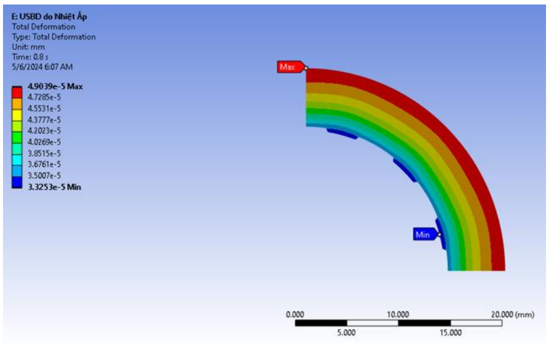
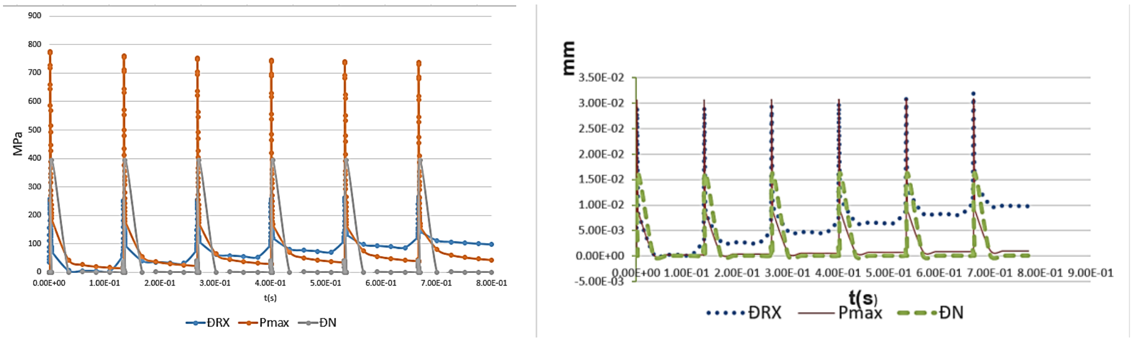


Figure 11. *Strain at cross-section DN.*

Over time, the maximum equivalent stress due to propellant gas pressure remains constant, while stress due to heat gradually increases as the temperature difference between layers becomes greater. Because the Von-Mises stress due to combined loading is equal to the stress due to pressure minus stress due to heat, the equivalent stress decreases with the number of shots (the new peak is lower than the old peak, figure 12b).



(a) Stress. *(b) Strain.*

Figure 12. *Stress (a) and strain (b) over time at cross-sections.*

When the number of shots increases to the point where there is no temperature difference, which means there is no thermal stress, the equivalent stress at this point will be equal to the stress caused by gas pressure. The maximum stress in the barrel wall caused by both temperature and gas pressure during 6 shots reaches 775 MPa in a very short time, which is about one ten-thousandth of a second (figure 12b). Given that the material's yield strength σb = 1080 MPa (at temperatures of 400 - 500 °C), the barrel remains durable during firing. However, some wear occurs in the rifling due to high temperature and the change rate of the gas flow, causing significant strain of the rifling region from the end of the combustion chamber to the position Pmax. At the same time, this region is also affected by the bullet's driving band, causing localized wear.

From the graph of maximum strain (figure 12a), we see that the strain caused by the combined load of the gun barrel when firing in continuous succession increases gradually with the number of shots fired. Over time, the external surface temperature also increases, causing the amplitude of the temperature difference after each shot to decrease. Therefore, we see that the strain of the barrel after each shot increases, but the amplitude of the increase gradually decreases. Although each new peak exceeds the magnitude of the previous one, the increase between consecutive peaks becomes progressively smaller, demonstrating a reduction in deviation as the loading cycles progress. When firing, the gradual increase in temperature causes the weakened mechanical properties of the barrel material, thereby increasing the strain of the barrel. This leads to the increasing dispersion of ammunition, affecting the technical performance of the weapon-ammunition system.

4. CONCLUSIONS

Based on the simulation results obtained using the finite element method in ANSYS Workbench, the observed phenomena of rifling wear and muzzle erosion during rapid firing can be explained as follows. Under high-temperature and high-velocity gas flow conditions, significant deformation occurs in the rifled region, extending from the rear of the chamber to the location where the propellant gas pressure reaches its maximum. The elevated thermal load softens the surface metal layer in this region, while the mechanical interaction with the projectile's driving band further promotes plastic flow of the material. The accumulation of these effects leads to localized wear and erosion of the barrel surface.

The obtained results provide a theoretical and computational basis for evaluating the structural strength and fatigue resistance of critical regions along the barrel wall during continuous firing.

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TÓM TẮT

Nghiên cứu trạng thái ứng suất biến dạng nòng pháo khi bắn liên thanh

Nghiên cứu này phân tích trạng thái ứng suất – biến dạng của nòng pháo trong điều kiện bắn liên thanh, sử dụng phương pháp phần tử hữu hạn (FEM) được triển khai trên phần mềm ANSYS Workbench. Kết quả tính toán được trình bày qua đồ thị, bản đồ phân bố và hình ảnh động theo thời gian, thể hiện sự phát triển của vùng tập trung ứng suất, biến dạng dẻo và trường nhiệt độ tại các vị trí xung yếu. Phân tích định lượng tác động của các chu kỳ áp suất và nhiệt độ cao lặp lại đến suy giảm vật liệu, hư hỏng mỏi và rút ngắn tuổi thọ nòng. Các kết quả thu được cung cấp cơ sở khoa học cho thiết kế, lựa chọn vật liệu, chế tạo và kiểm bền nòng pháo hiện đại.

Từ khoá: Nòng pháo; Trạng thái ứng suất; Bắn liên thanh; ANSYS.