Engineering and Technology Journal e-ISSN: 2456-3358
Volume 08 Issue 08 August -2023, Page No.- 2556-2564
DOI: 10.47191/etj/v8i8.09, I.F. – 7.136

Studying the Effect of Rifling Parameters on the Stress State in a Gun Barrel Wall When Firing

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ABSTRACT: The problem of determining the stress state of the rifled-bore barrel when firing was presented in this article. Where the effects of rifling parameters such as the quantity of grooves n, groove width a, depth of groove t, radius of groove corner ρ were investigated. A rifled-bore barrel has been modeled and investigated by using Ansys software on the basis of finite element method. The problem has only been treated under pressure load in static case. The article can be used for reference to improve the accuracy in calculating design and manufacturing gun barrel.

KEYWORDS: the stress state, the rifled-bore barrel, the rifling parameters

1. INTRODUCTION

A barrel is an integral part of a gun and that is the main and most important part of the gun. The design of the barrel is an important first issue, which raises the following problems that we can design other parts of the barreled weapon system. The barrel usually consists of two components: the chamber and the bore - the guide part. For artillery guns that use the ammunition stabilized according to the spinning principle, the guide part of the barrel has helical grooves (riflings).

In the computational literature of the artillery design, the barrel was considered as a thick cylinder, and then, rifling parameters were chosen according to experience and applied their effects to the strength of barrel in the form of safety coefficient [1-4]. First, Lame's equation was applied by the authors in some works to calculate the endurance of tubes subjected to internal pressure only [5, 6]. Later, this method was extended to the case of unevenly heated cylinders [7-9]. The work [7] presented a method for calculating the stress of a gun barrel under the combined thermo-mechanical load, namely the contact and friction loads of the bullet and the heat and pressure of the powder gas. Authors also considered the effect of high temperature on the mechanical properties of the barrel via the finite element method, which led to the requirement that the barrel should have the better circumferential yield strength. The thermo-mechanical analysis of the strength deterioration of this barrel material during continuous firing was studied. The finite element models were established using Abaqus software for the increase of the temperature and stress of the inner bore wall beared to cyclic loads. Results shown that the stress exceeded the yield strength of $30SiMn_2MoVA$ gun barrel steel [8]. In the other work, the thermo-mechanical combination theory was handled for the 3-D transient heat transfer and stress analysis. The value of the powder gas pressure with Noble–Abel equation was used to determine the temperature of the powder gas along the bore. Using Vielle's burning equation determined the convection heat transfer coefficient and ANSYS model was employed to obtain the temperature distribution in the radial and axial directions of the barrel [9]. In fact, with the rifled-bore barrel, the stress state in the barrel wall is different from the stress state inside the cylinder wall due to the stress concentration [10]. For gun barrels, because of the temperature gradients and repetitive high-pressure impulses, erosions can be practically induced. At those erosions, due to stress concentration, cracks can readily initiate and propagate. The Bauschinger Effect on the stress intensity factors was investigated for a crack originating from an erosion's peak in a pressurized thick-walled cylinder. A two-dimensional model, based on ANSYS sofwear, according to von Mises yield criterion, is simulated by thermal loading and the stress intensity factors are determined by the nodal displacement method [11]. A steel cannon barrel was assumed to have a smooth inner surface to predict its lifetime. The finite element analyses were carried out in order to determine the stress intensity factor as a function of crack length, that was assumed to follow the Paris–Erdogan law [12]. The influence of structural parameters on the performance of high-pressure and high-temperature powder gas operated guns is critical to the design. A combined pooled parameter model was used to predict the propellant combustion, and a dynamic finite element method was applied to approximate the mechanical interactions between the bullet and the barrel. However, the results only shown the effect of the bullet's rotational band width [13], or the effects of the height, pitch and shape of a rib on the heat transfer performance in circumferentially non-uniformly heated rifled tubes were studied [14]. In addition, the effects of different rifling (rib rifling, increasing rifling or combined rifling) on rotating band are also investigated [15].

The inner surface of a gun barrel is subjected to the complex effects of cyclic high-temperature and pressure loads during the continuous firing process, resulting in the existence of a complex stress state inside the barrel wall. The correlation between the ballistic performances and the stress state is an important issue for improving barrel life. This article provides a method to investigate the influence of helical groove parameters on the stress state of the gun tube and gives a reasonable rifling structure.

2. THE STRESS STATE IN THE RIFLED-BORE WALL

2.1. Assumptions

- The material for manufacturing the barrel is homogeneous and isotropic, the deformation is small within the elastic limit, the stress and strain relationship obeys Hooke's law.
- Considering the cross section at a sufficiently large distance from the muzzle to ensure that the plane and relative deformation due to axial temperature are constant. Therefore, the problem solving leads to the solution of a planar problem with a flat deformation state.
- The pressure and temperature acting on the part are variable fields, but the load is assumed to be semi-static.
- Pressure is evenly distributed and acts perpendicular to the inner surface of the barrel wall. Under the effect of pressure the points on the barrel wall are in equilibrium.
- The temperature T in the barrel wall is symmetrically distributed across the axis and varies with the thickness but does not change with the length of the barrel.
- The dynamic boundary conditions are ignored.

The model is as shown in Figure 1:

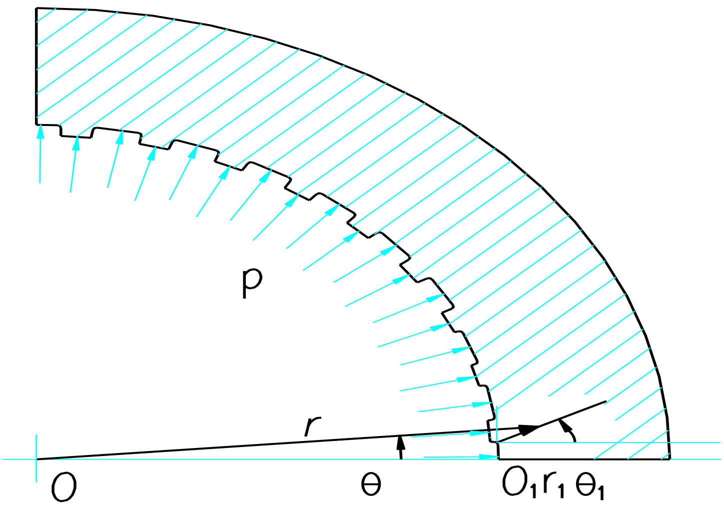

Fig 1. The problem model of barrel under internal pressure

2.2. The stress state in the rifled-bore wall

The constitutional relations describing the thermoelastic-plastic deformation of the material have the form [5, 16]:

$$\begin{aligned} &\varepsilon_{mn} = 0.5\left(\partial u_n/\partial x_m + \partial u_m/\partial x_n\right); \quad \varepsilon_{mn} = \varepsilon_{mn}^e + \varepsilon_{mn}^p; \quad \varepsilon = \varepsilon_{mm}/3; \\ &\Delta T = T - T_0; \quad \sigma_{mn} = 3E\left(\varepsilon - \alpha\Delta T\right)\delta_{mn} + 2G\left(\varepsilon_{mn}^e - \varepsilon\delta_{mn}\right); \\ &\sigma = \sigma_{mm}/3; \quad d\varepsilon_{mn}^p = d\lambda\left(\sigma_{mn} - \sigma\delta_{mn}\right) \end{aligned} \tag{1}$$

Where $x_{m,n}$ are the Cartesian coordinates, $u_{n,m}$ are the displacement vectors, ε_{mn} is the strain tensor, ε_{mn}^e is the elastic strain tensor, ε_{mn}^p is the plastic strain tensor, T is the temperature, T_0 is the initial temperature, ΔT is the temperature increment, σ_{mn} is the stress tensor, E, G are the elastic moduls, α is the linear expansion coefficient, δ_{mn} is the Kronecker symbol, ε, σ are the average strain and stress, $d\lambda$ is an indeterminate factor. Under active loading, the von Mises yield condition is satisfied [16] :

$$\left(\sigma_{mn} - \sigma\delta_{mn}\right)\left(\sigma_{mn} - \sigma\delta_{mn}\right) \le 2\sigma_y^2/3 \tag{2}$$

In the case of neutral loading or under purely elastic deformation and unloading case, $d\lambda=0$.

The variational equation:

$$\int_S \sigma_{mn}\delta\varepsilon_{mn} dS = \int_l p_k \delta u_k dl \tag{3}$$

Where S is the cross-sectional area of the bore, l is its boundary contour, p_k is the vector of the load applied to the contour. The temperature function T of the bore wall is a function of radius r according to the logarithmic law:

$$T = T_2 + (T_1 - T_2)\frac{\ln(r/R_2)}{\ln(R_1/R_2)} \tag{4}$$

The problem is non-linear. Its solution is found by the iterative method of elastic solutions [5]. Stresses are presented as a sum:

$$\sigma_{mn} = t_{mn} - 3E\alpha\Delta T\delta_{mn} + s_{mn} \tag{5}$$

Where the stress tensor t_{mn} is related to the strain tensor by Hooke's law, and the initial stress tensor s_{mn} is proportional to the plastic strain tensor:

$$t_{mn} = 3E\varepsilon\delta_{mn} + 2G(\varepsilon_{mn} - \varepsilon\delta_{mn}); \quad s_{mn} = -2G\varepsilon^{p}_{mn} \tag{6}$$

The variational equation (3) is transformed to the form:

$$\int_S t_{mn}\delta\varepsilon_{mn}dS = \int_l p_k\delta u_k dl + \int_S (3E\alpha\Delta T\delta_{ij} - s_{ij})\delta\varepsilon_{ij}dS \tag{7}$$

Solving the stress problem in the barrel wall can use numerical methods based on finite element theory [17]. The root singularity of stresses and strains is taken into account by adding additional functions taken from the asymptotic solution of the problem of linear fracture mechanics, which is proportional to the stress intensity factors [18].

Stresses, strains and displacements are determined by asymptotic formulas [18]:

$$\sigma_{mn} = K\sigma^*_{mn}; \quad \varepsilon_{mn} = K\varepsilon^*_{mn}; \quad u_m = Ku^*_m \tag{8}$$

Where K is the stress intensity factor. In particular, for plane deformation:

$$\begin{aligned} u^*_1 &= \frac{2(1+\nu)}{E}\sqrt{\frac{r}{2\pi}}\cos\frac{\theta}{2}\left(1 - 2\nu + \sin^2\frac{\theta}{2}\right) \\ u^*_2 &= \frac{2(1+\nu)}{E}\sqrt{\frac{r}{2\pi}}\cos\frac{\theta}{2}\left(2(1-\nu) - \cos^2\frac{\theta}{2}\right) \end{aligned} \tag{9}$$

Where E is Young's modulus, ν is Poisson's ratio.
Movements within any finite element are given as:

$$u_m = L_i(\xi)L_j(\eta)U^{ij}_m + K_{\mathrm{I}}u^*_m \tag{10}$$

The original variational equation (3), written for one element, is reduced to the form:

$$\begin{aligned} &\Big\{a_0\big[(1-\nu)a_{ijmn} + 0.5(1-2\nu)b_{ijmn}\big]U^{mn}_1 + a_0\big[\nu c_{ijmn} + 0.5(1-2\nu)c_{mnij}\big]U^{mn}_2 + \\ &+(d_{ij11} + e_{ij12})K_{\mathrm{I}}\Big\}\delta U^{ij}_1 + \Big\{a_0\big[\nu c_{mnij} + 0.5(1-2\nu)c_{ijmn}\big]U^{mn}_1 + \\ &+a_0\big[(1-\nu)b_{ijmn} + 0.5(1-2\nu)a_{ijmn}\big]U^{mn}_2 + (e_{ij22} + d_{ij12})K_{\mathrm{I}}\Big\}\delta U^{ij}_2 + \\ &+\Big\{a_0\big[(1-\nu)f_{mn11} + \nu f_{mn22} + (1-2\nu)g_{mn12}\big]U^{mn}_1 + a_0\big[(1-\nu)g_{mn22} + \\ &+\nu g_{mn11} + (1-2\nu)f_{mn12}\big]U^{mn}_2 + hK_{\mathrm{I}}\Big\}\delta K_{\mathrm{I}} = \chi_{ij}\delta U^{ij}_1 + \psi_{ij}\delta U^{ij}_2 + \omega\delta K_{\mathrm{I}} \end{aligned} \tag{11}$$

Where the coefficients are determined by the formulas:

$$a_0 = \frac{E}{(1-2\nu)(1+\nu)}; \quad a_{ijmn} = \int_S \Phi_{ij}\Phi_{mn} dS; \quad b_{ijmn} = \int_S F_{ij}F_{mn} dS;$$
$$c_{ijmn} = \int_S \Phi_{ij}F_{mn} dS; \quad d_{ijmn} = \int_S \Phi_{ij}\sigma^*_{mn} dS; \quad e_{ijmn} = \int_S F_{ij}\sigma^*_{mn} dS;$$
$$f_{ijmn} = \int_S \Phi_{ij}\varepsilon^*_{mn} dS; \quad g_{ijmn} = \int_S F_{ij}\varepsilon^*_{mn} dS; \quad h = \int_S \sigma^*_{mn}\varepsilon^*_{mn} dS; \tag{12}$$
$$\chi_{ij} = \int_l p_1 L_i(\xi) L_j(\eta) dl - \int_S \left[(3K\alpha\Delta T + s_{11})\Phi_{ij} + s_{12}F_{ij} \right] dS;$$
$$\psi_{ij} = \int_l p_2 L_i(\xi) L_j(\eta) dl - \int_S \left[s_{12}\Phi_{ij} + (3K\alpha\Delta T + s_{22})F_{ij} \right] dS;$$
$$\omega = \int_l p_m u^*_m dl - \int_S (3K\alpha\Delta T\delta_{mn} + s_{mn})\varepsilon^*_{mn} dS$$

The contour integrals in formulas (12) are nonzero only for elements whose sides are subjected to an external load. The functions included in the integrands of the coefficients (2.11) are found from the expressions:

$$\Phi_{ij}(\xi,\eta) = 0.5\left[(-1)^i L_j(\eta)\partial_1\xi + (-1)^j L_i(\xi)\partial_1\eta \right];$$
$$F_{ij}(\xi,\eta) = 0.5\left[(-1)^i L_j(\eta)\partial_2\xi + (-1)^j L_i(\xi)\partial_2\eta \right]; \quad \partial_m = \partial/\partial x_m;$$
$$\begin{pmatrix} \partial_1\xi & \partial_2\xi \\ \partial_1\eta & \partial_2\eta \end{pmatrix} = \begin{pmatrix} \partial_\xi x_1 & \partial_\eta x_1 \\ \partial_\xi x_2 & \partial_\eta x_2 \end{pmatrix}^{-1}; \quad \partial_\xi x_m = 0.5(-1)^i L_j(\eta) X^{ij}_m; \tag{13}$$
$$\partial_\eta x_m = 0.5(-1)^j L_i(\xi) X^{ij}_m$$

2.3. Example of stress state for 122mm cannon barrel

Use Ansys software to review the stress state for a section [19]. Calculations were performed with the following initial data:

Geometric parameters of the detail: inner radius: r_1 = 61 mm, outer radius: r_2 = 95 mm;

Material parameters: Young elastic modulus: $E_0 = 2.1*10^5$ N/mm2, Poison coefficient: ν = 0.3;

Load parameter: pressure is taken from the results of the internal ballistic [1]:

d = 122 mm; ω = 4,48 kg; Λ_∂ = 5,662; Wo = 7,11 dm^3; q = 22 kg; χ = 1,17; Δ = 0,63 kg/dm^3 ; l_∂ = 33,52 dm ; B = 2,076; nitrocellulose propellant.

At standard temperatures (+15^{o}C), t_3 = +50^{o}C và t_3 = -50^{o}C, we can construct the maximum powder gas pressure curve in the bore (Fig. 2).

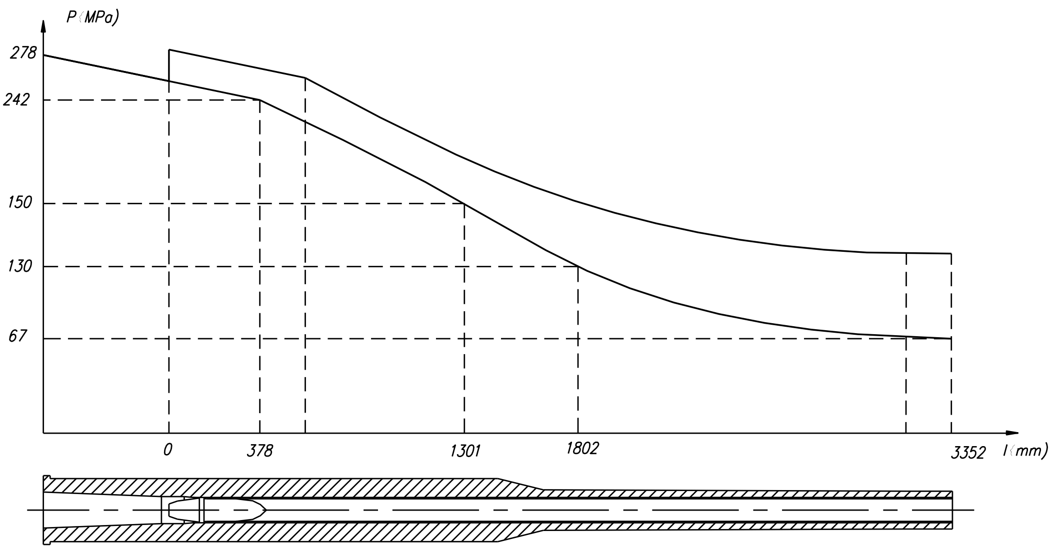

Fig. 2. The maximum powder gas pressure curve in the bore

When the temperature changes, Young elastic modulus takes the form:

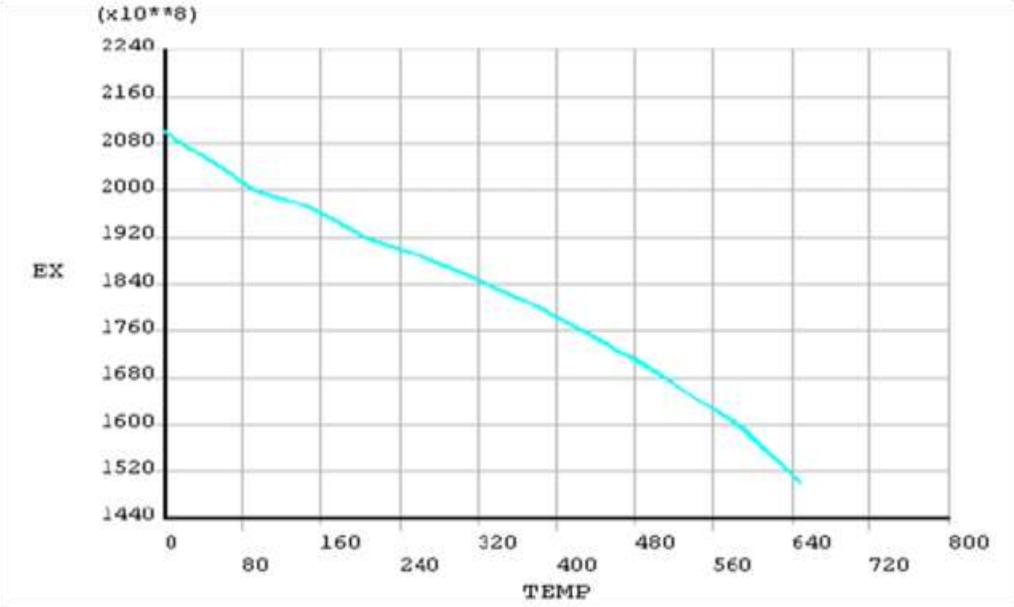

Fig. 3. The dependence of Young elastic modulus on temperature

With the given parameters, the calculation result for the stress state of the smooth-bore are shown in Fig. 4.

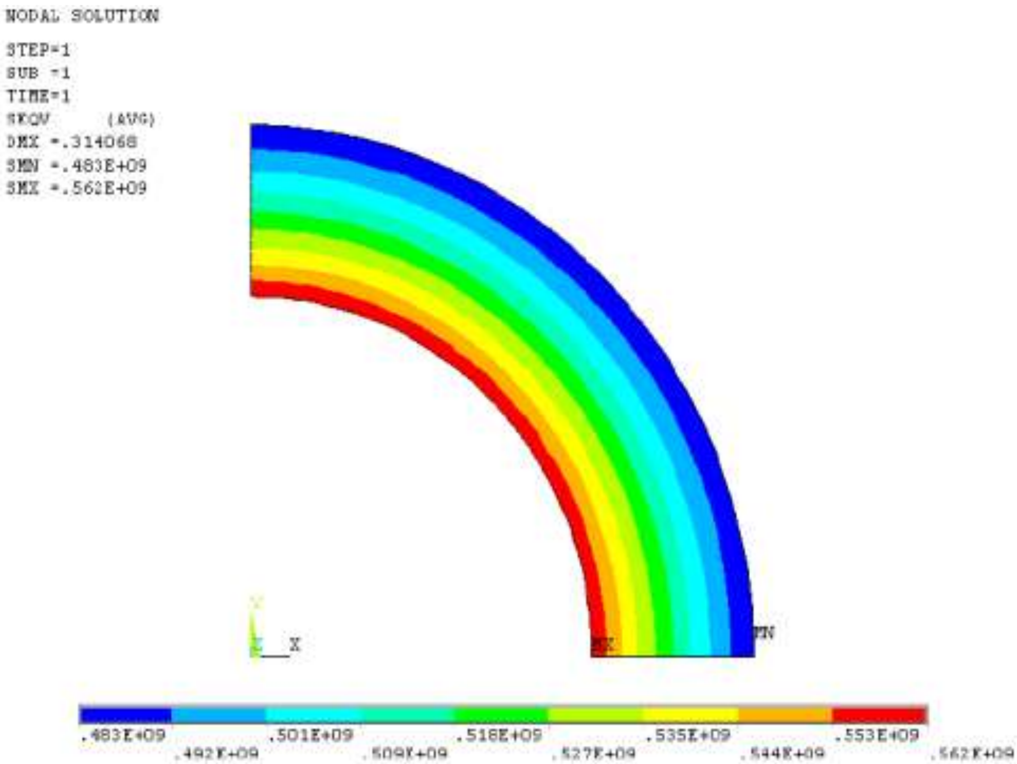

Fig. 4. Stress state of 122 mm cannon barrel with smooth-bore.

When the helix groove is included, with the groove parameters: number of helix grooves n = 36, groove width a = 6.6 mm, land width b = 4.04 mm, groove depth t = 1 mm, groove corner radius ρ = 0.5 mm. The stress state calculation is shown in Fig. 5.

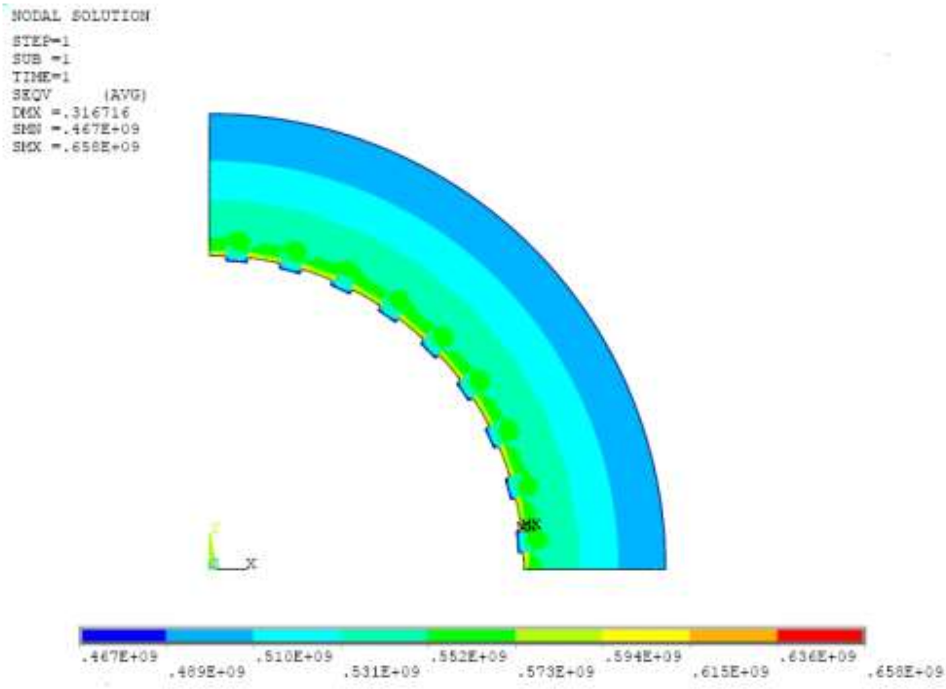

Fig. 5. Stress state of 122 mm cannon barrel with spiral groove

As can seen that, the maximum stress in this case is 1.17 times larger than the smooth-bore case and the minimum stress is also smaller, equal to 0.97 times. The maximum stress is concentrated at the corner of the spiral groove, the minimum stress is concentrated at the top of the land.

3. THE EFFECTS OF RIFLING PARAMETERS ON THE STRESS STATE IN THE BARREL WALL

Rifling is the process of making spiral grooves in the barrel of a gun, which imparts a spin to a projectile around its long axis. This spin serves to gyroscopically stabilize the projectile, improving its aerodynamic stability and accuracy. A diagram of riflings is showed below:

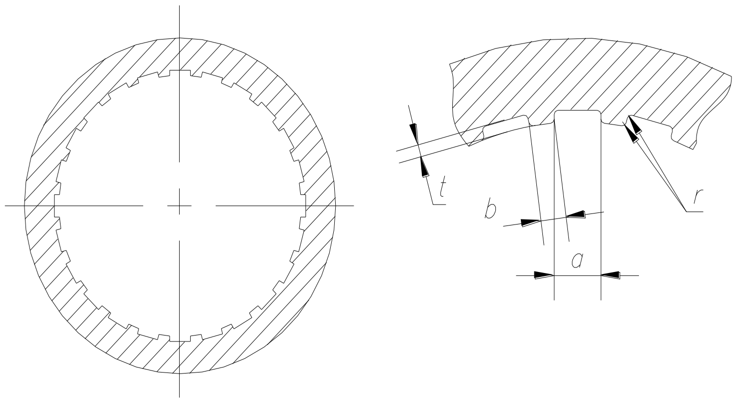

Fig. 6. Schematic of riflings

The influence of the parameters is considered for each parameter:

3.1. Depth of the rifling (t)

The depth of the rifling is related to the strength of the rifling land and the shell belt as well as the wear resistance of the rifling. When designing it is chosen by experience. The groove depth of the current barrel is determined by the correlation: $t = (0{,}01 \div 0{,}025)d$, where d – caliber, *mm*.

The effect of the groove depth on the stress state of the 122 mm cannon tube section is shown in Fig. 7.

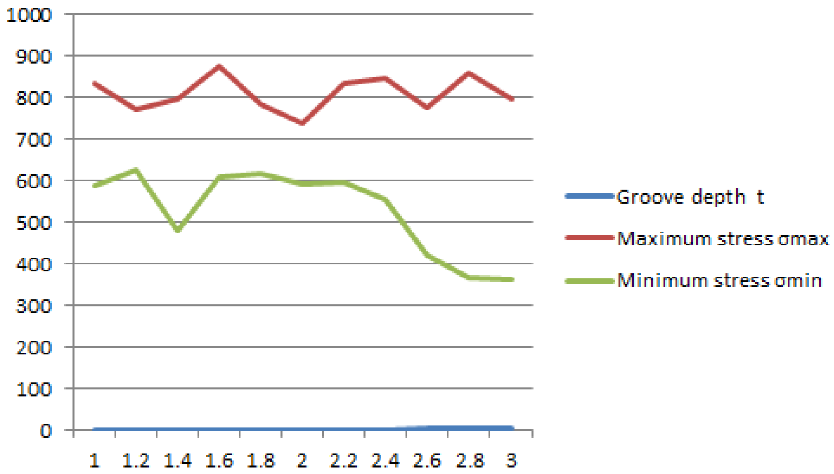

Fig. 7. Influences of groove depth (t) on the stresses σ_{max} and σ_{min}

3.2. Width of the rifling (a)

The width of the groove a is geometrically related to the land width b because of $a+b = \pi d/n$, on the other hand, ensures the strength of the rifling land under the effect of the belt force. According to experience, we choose:

- For gun systems with $v_o = 800 \div 1000$ *m/s*, $a = (1.5 \div 1.8)b$;
- For powerful guns with $v_o > 1000$ *m/s*, $a = (1{,}1 \div 1{,}4)b$.

The effect of the groove width on the stress state is shown in Fig. 8.

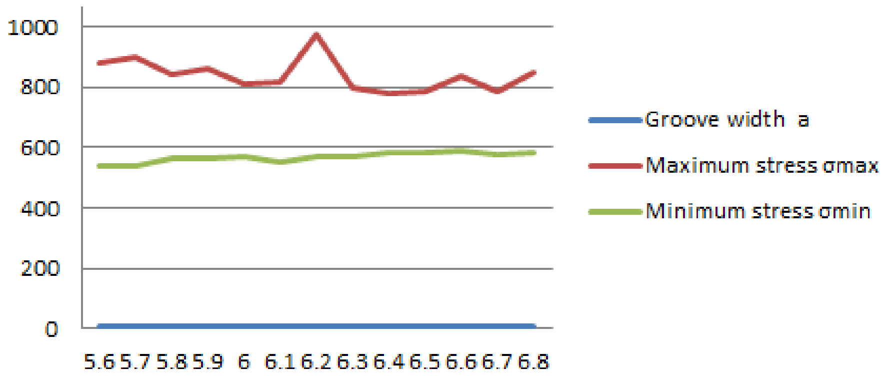

Fig. 8. Influences of groove width (a) on the stresses σ_{max} and σ_{min}

3.3. Quantity of the grooves (n)

With selected depth, the quantity of the grooves is chosen so that the specific pressure of the shell belt on the tightening wall of the land does not exceed the allowed value. Experimental quantity of grooves is chosen by caliber as follows:

$n = 4d$ for cannons;

$n = 3d$ for howitzers.

The effect of the quantity of spiral grooves on the stress state is shown in Fig. 9.

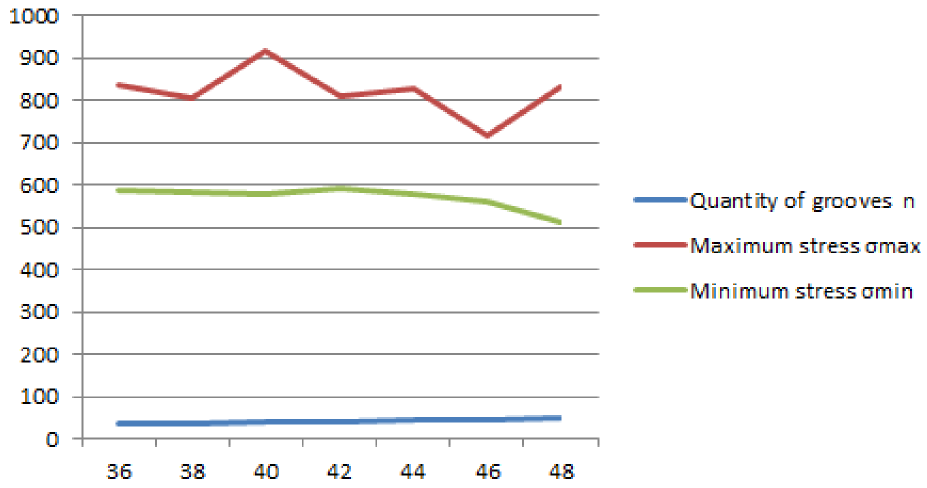

Fig. 9. Influences of grooves quantity (n) on the stresses σ_{max} and σ_{min}

3.4. Radius of groove corner (ρ)

This radius depends on the manufacturing technology, it is the profile angle of the cutting tool. Smaller radius ensures reliability when guiding projectile but difficult in manufacturing and on the contrary. This radius is usually no larger than 3 mm. The effect of groove corner radius on the stress state is shown in Fig. 10.

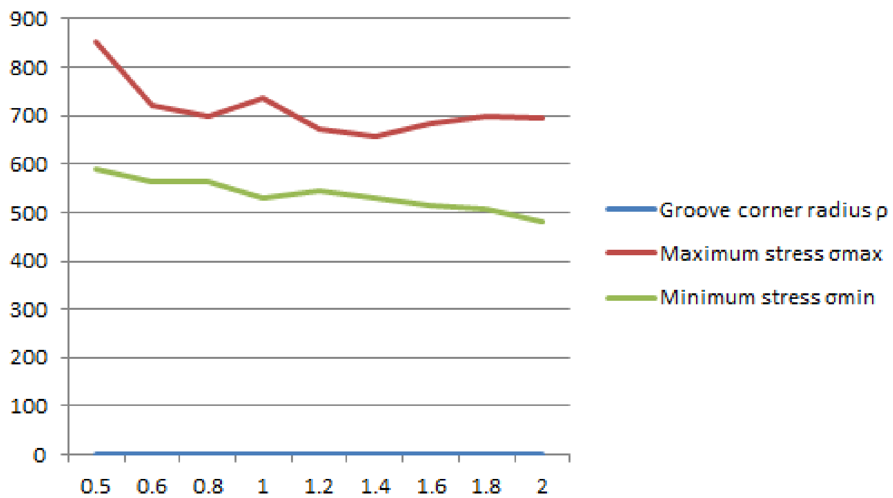

Fig. 10. Influences of groove corner radius (ρ) on the stresses σ_{max} and σ_{min}

4. CONCLUSION

The problem has been treated under pressure load in static case. The results showed that twist grooves had a significant influence on the stress state inside the barrel wall. Under the influence of gas pressure load, the barrel has stress concentration and uneven stress distribution inside the barrel wall. The maximum stress at the corners of the helical grooves and the minimum stress at the top of the lands. Their value depends on the stress intensity factor. Experiments show that the stress intensity coefficient depends on the conformational change of the helical groove $\left(\frac{t}{\Delta r}, \frac{a}{t}, \frac{d}{2\Delta r}\right)$ (Δr _ the thickness of the barrel wall) [20].

A growth of the rifling depth reduces the stress at the rifling land, thereby increasing the barrel life but also rising the belt cutting force, which is difficult in manufacturing technology and complicated in the exploitation. When the corner radius goes up, both the stress at the rifling land and the groove corner reduce but which causes belt glide. Increasing the number of helical grooves slightly reduces the stress at the rifling land, but the number of these grooves is related to the groove width, the land width and land durability. An expansion of the groove width leads to a decrease in the stress at the groove corner but a reduction of the land width and an increase in the stress at the top of the rifling land. However, besides the requirement for durability, the barrel has other requirements. In fact, the 122 mm cannon has two models, M30 and D30, with different barrel structures serving two different tactical purposes.

REFERENCES

1. Khong Dinh Tuy et al., *Artillery system design base*, Military Technical Academy, 2009 (in Vietnamese).
2. Phan Nguyen Thieu, Khong Dinh Tuy, *Design principles of barreled weapons*, People's Army Publishing House, 2000 (in Vietnamese).
3. Orlov B.V., *Design of rocket and barreled systems*, Mechanical engineering, Moscow, 1974 (in Rusian).
4. Chuev Yu.V. , *Design of barreled complex*, Mechanical engineering, Moscow, 1976 (in Rusian).
5. Lavit I.M., Tolokonnikov L.A., Low-cycle fatigue of hollow cylinders loaded with internal pressure, Izv. TulGU, *Problems of special engineering*, 1997, Issue 1, pp. 124-128 (in Rusian).
6. Ge Shuqiang et al., Strength and Modal Analysis of a Gun Barrel under Four Different Strength Theories, *International Symposium on Advanced Launch Technologies (ISALT 2022), Journal of Physics: Conference Series*, 2023, doi:10.1088/1742-6596/2460/1/012058
7. Yuzhao Yang et al., Dynamic stress analysis of anisotropic gun barrel under coupled thermo-mechanical loads via finite element method, *Latin American Journal of Solids and Structures*, 2020, 17(1), e243, https://doi.org/10.1590/1679-78255800
8. Junyu Chen et al., Thermo-mechanical analysis of strength degradation of $30SiMn_2MoVA$ gun barrel material during continuous shooting, *Engineering Failure Analysis*, Volume 139, 2022, https://doi.org/10.1016/j.engfailanal.2022.106438
9. Abdullah Şentürk, Halil Işık, Celal Evci, Thermo-mechanically coupled thermal and stress analysis of interior ballistics problem, *International Journal of Thermal Sciences*, Volume 104, 2016, pp. 39-53, https://doi.org/10.1016/j.ijthermalsci.2015.12.019
10. Bui Quy Viet, Research on stress state of cannon barrel with spiral groove when firing, *Vietnam Mechanics Journal*, 2014 (in Vietnamese).
11. Q. Ma, C. Levy, M. Perl, Stress Concentration and Stress Intensity for Pressurized Eroded Autofrettaged Thick Cylinders With Bauschinger Effect , *ASME 2010 Pressure Vessels and Piping Division/K-PVP Conference*, 2010, https://doi.org/10.1115/PVP2010-25607
12. Leslie Banks-Sills, R. Eliasi, Fatigue life analysis of a cannon barrel, *Engineering Failure Analysis*, Volume 6, Issue 6, 1999, pp. 371-385, https://doi.org/10.1016/S1350-6307(98)00054-5
13. Chao-bin Hu, Xiao-bing Zhang, Influence of multiple structural parameters on interior ballistics based on orthogonal test methods, *Defence Technology*, Volume 15, Issue 5, 2019, pp. 690-697, https://doi.org/10.1016/j.dt.2019.06.014
14. Junping Gu et al., Geometry optimization for supercritical water heat transfer enhancement in non-uniformly heated rifled tubes, *Applied Thermal Engineering*, Volume 187, 2021, https://doi.org/10.1016/j.applthermaleng.2021.116566
15. Jia Sun et al., Analysis of gun barrel rifling twist, *AIP Conference Proceedings*, 2017, https://doi.org/10.1063/1.4982461
16. Hoang Xuan Luong et al., *The theory of elasticity - plasticity – creep*, Military Technical Academy, 2008 (in Vietnamese).
17. Zienkiewicz O.C., Taylor R.L., *The finite element method*. Oxford: Buttenworth, Heinemann, 2000.
18. Krukova N.V., Lavit I.M., The finite-element method in linear fracture mechanics problems // *Proceedings of 3rd European Conference on Computational Mechanics*, Lisbon: ECCM ,CD-ROM Proc, 2006.
19. Morozov E.M., Muizemnek A.Yu., Shadsky A.S., *Ansys in the hands of an engineer: Fracture mechanics*, Lenand, Moscow, 2008 (in Rusian).
20. Laham S.Al., *Stress Intensity Factor and Limit Load Handbook*, British Energy Generation Ltd, United Kingdom, 1999.