UDK: 537.312.9:531.57:517.925.7:"LAME"
COSATI: 19-10
doi: 10.5937/str2002041B

The Influence of the Internal Ballistic Pressure on the Rifled Barrel Stress Response

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This paper focused on the 12.7 mm gun barrel stress response caused by the pressure of the gunpowder gases. During the firing process, the barrel is loaded by different mechanical, chemical and thermal loads. In this paper except the pressure of the propellant combustion, all the other loads were ignored. The pressure loads are obtained with a mathematical model of the interior ballistic. The Lame equations for the thick-walled cylinder were used to calculate the barrel stress response. The loads are applied on a certain barrel cross-section for a defined time. Two 3D models of the barrel with and without grooves were used to perform a numerical simulation. A comparison between results for the two types of barrels shows a good agreement between the stresses obtained by the analytical and numerical methods.

Key words: **stress response, barrel, internal ballistics, Lame equations.**

Introduction

DESIGNING guns is a matter of great importance due to the fact that it is the main tool for defending people. The design of weapons requires a deep knowledge in the science of ballistics. The internal ballistics studies the phenomena that occur inside the barrel, when the projectile is accelerated from zero to its initial velocity at the muzzle of the barrel.

One of the aims of solving the internal ballistic problems is to get a specific muzzle velocity without damaging the weapon from excess internal barrel pressure.

The present work is focused on the stress response of a 12.7 mm gun barrel caused by the pressure of the gunpowder gases during the firing process. The pressure loads are obtained with the numerical two-phase flow model. The stresses in the barrel are approximately calculated with analytical equations, they are also obtained by means of 2D and 3D transient structural simulations. The compatibility between the simulations results and the analytical calculations is investigated.

Different loads types on the interior of the barrel

During the internal ballistic process, various phenomena occur in a brief amount of time, like propellant burning, energy conversion, and projectile movement. The stresses in the barrel caused by those phenomena are the results of different loads. The main loads are the chemical, thermal and mechanical loads generated by the combustion of the propellant:

- The friction forces between the projectile and the lands of the barrel.
- Loads caused by the gravity.
- The pressure of the propellant combustion.

For reasons of simplification in this study, we will be interested only in the stresses caused by the generated pressure of the propellant combustion. All other loads are neglected. The bullet and the bullet cartridge are not considered in the present work.

Internal ballistics equations and models

Based on the energy, momentum, and mass conservation equations, the process of propellant combustion in the internal ballistic domain was described several times by mathematical models to anticipate the internal ballistic parameters. The classical theory introduced by Nikolai Fedorovich Drozdov [1] allows to describe the combustion of a single gunpowder grain with a particular geometric shape. This classical theory considers that the combustion gases spread behind the projectile according to the adiabatic law. It also considers that the pressure has the same value in all the barrels interior points behind the projectile at a given time.

The method used to obtain the internal ballistic mathematical models for this study is the two-phase flow method [2, 3]. Unlike the first method, this method takes into account the speed of the gases and solids (the grains of the powder) inside the barrel. It is based on the same single gunpowder grain geometric combustion law, applied on a division of the volume. The values of the pressures behind the projectile obtained by this model are not the same at a specified time as it is shown in Fig.1.

The mathematical model was programmed in the Matlab software, and by introducing the input parameters related to the propellant, the projectile and the 12.7 mm caliber barrel, the theoretical pressure values produced by the combustion were obtained. Fig.1 shows a 3D plot of the produced pressure as a function of time and position.

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Presented as Paper 087 at the 9th International Scientific Conference on Defensive Technologies, Belgrade, Serbia, 15-16 October 2020
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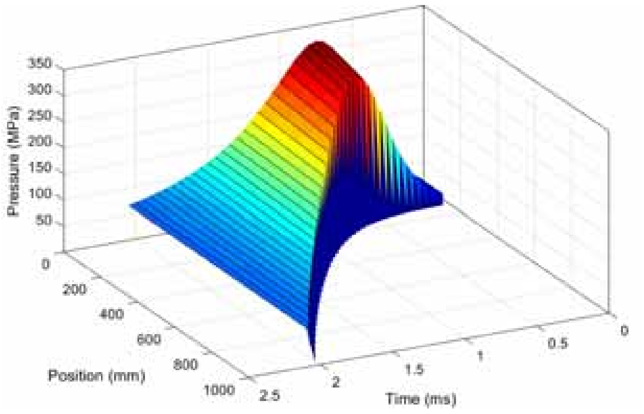

Figure 1. Pressure function of time and position

Analytical model of the stress in the barrel

The interior of the barrel is designed with helicoidal grooves to give a specific angular velocity to the projectile. Unfortunately, for this complex geometry, there is no analytical formula to calculate its radial, tangential and axial stresses caused by the combustion of the propellant.

To calculate approximately the stresses, the barrel is considered as a thick-walled cylinder, the hoop and the radial stresses are given by [4]

$$\sigma_h = A + \frac{B}{r^2} \quad (1)$$

$$\sigma_r = A - \frac{B}{r^2} \quad (2)$$

where

$$A = \frac{P_i r_i^2 - P_0 r_0^2}{r_0^2 - r_i^2} \quad (3)$$

$$B = \frac{(P_i - P_0) r_0^2 r_i^2}{r_0^2 - r_i^2} \quad (4)$$

σ_h : Hoop stress.
σ_r : Radial stress.
P_i : Internal pressure.
P_0 : External pressure.
r_i : Internal radius.
r_0 : External radius.
r : Radius at the point of interest.

Figures 2 and 3 represent the radial and hoop stresses of two barrels sections at different times. The sections are situated at different distances from the bottom of the barrel. The following table (Table 1) represents the data needed to calculate the stresses. The value of the internal pressure applied to a specific section at some point in time is obtained from the mathematical model results.

Table 1. Applied pressures

Time(ms)	section z (mm)	interior radius (mm)	exterior radius (mm)	pressure (MPa)
0.5	100	6.4	21	207.11
1.2	350	6.4	15.4	223.14

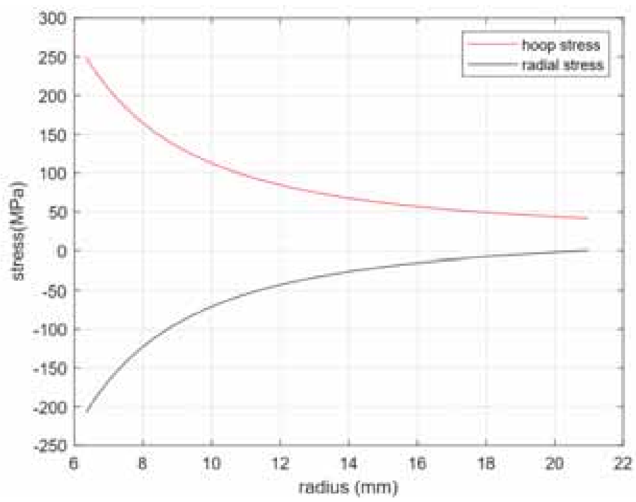

Figure 2. Stresses in sections 100 mm at 0.5 ms

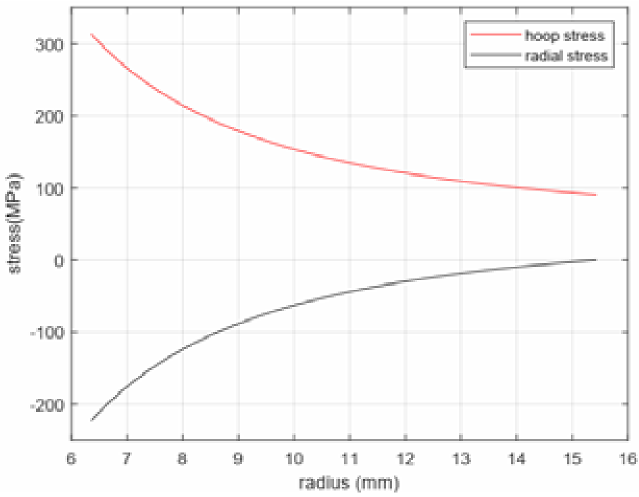

Figure 3. Stresses in sections 350 mm at 1.2 ms

The absolute values of the intensities of the radial and tangential stresses are higher on the interior walls of the barrel and then they decrease to their minimum values on the exterior walls of the barrel.

Numerical simulations of the stress in the barrels

To investigate the stresses in the barrel 2D and 3D simulations were performed in the software Abaqus [5]. For the 2D simulations the CAD model consists of a 12.7 mm interior diameters discs (with and without grooves), the outer diameter is 21 mm and 15.4 mm for the sections situated at 150 mm and 350 mm respectively. The mesh used is a structural mesh. The loads are applied on the interior circles of the discs as pressure loads. Fig.4 shows the used mesh for the 2D simulations.

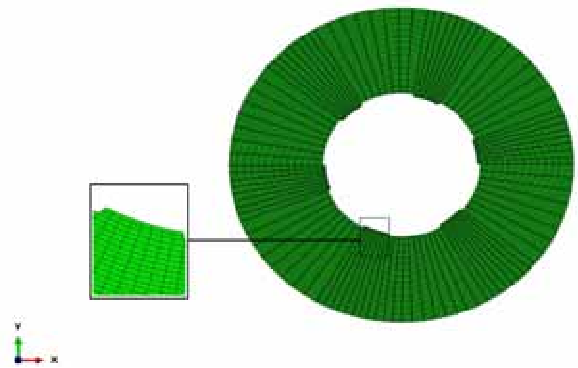

Figure 4. Structured Mesh for the Section 350 mm

For the 3D simulations two CAD models of the barrel with and without grooves were used to perform the numerical simulations. Figures 5 and 6 shows the CAD model for the barrel without grooves and the barrel with grooves respectively.

Figure 5. CAD models of the barrel without grooves

Figure 6. CAD models of the barrel with grooves

The CAD models were imported to the FEM structural analysis software, the mesh type used is a free mesh with tetrahedron element type.

To apply the time-space dependent loads multiple steps were created in the Abaqus step manager, from another hand the interior surfaces of the barrel are partitioned using datum plans at specified distances from the bottom of the barrel. A specific time is introduced as a period for each step, in each step the pressure load is applied on a group of internal surfaces to simulate the moving loads. As an initial boundary conditions, the rear surface of the barrel is fixed. Fig.7 shows the partitioned interior surfaces of the barre. Fig.8 shows the loads applied on the interior surfaces for the time 0.9 ms.

Figure 7. Interior barrel's surface partitions

Figure 8. Applied loads on the interior surfaces

Discussion of results

Figures 9 to 11 represents the visualization of the equivalent von Mises stress distribution obtained from the 2D simulations for the sections with and without grooves.

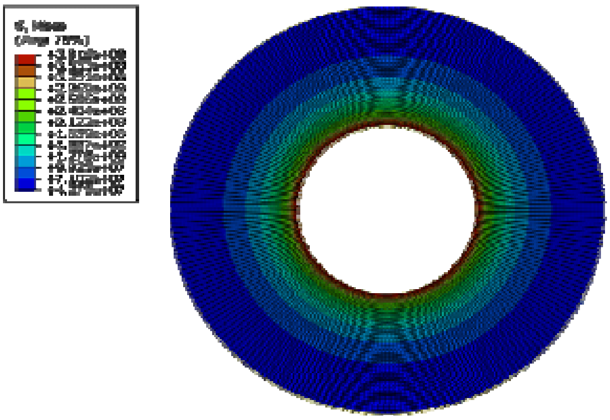

Figure 9. Equivalent von Mises stress for the section 100 mm at 0.5 ms

The barrel is grooved from the end of the combustion chamber to the muzzle, the length of the combustion chamber is the same as the bullet cartridge (108 mm).

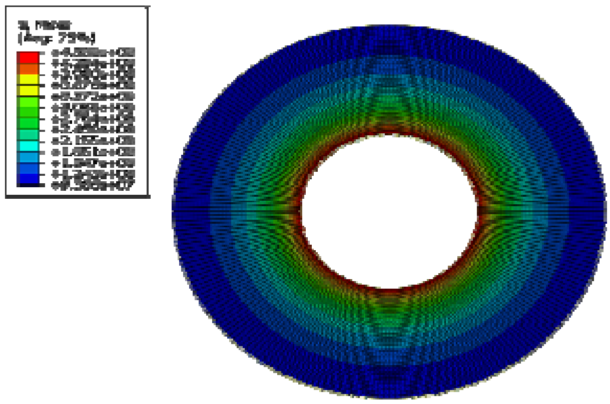

Figure 10. Equivalent von Mises stress for the section 350 mm without grooves at 1.2 ms

Since the grooves start at 108 mm from the bottom of the barrel, the 2D simulation for the section 100 mm with grooves is not needed.

The simulation output is the equivalent von Mises stresses obtained for each node of the FEM model. The data are exported as a text file, and treated to draw the graphs of the equivalent von Mises stresses as a function of the radius.

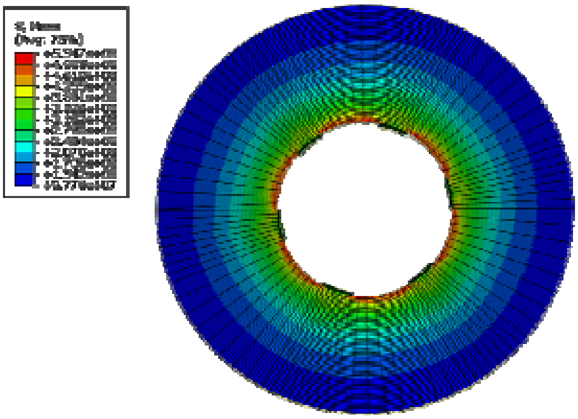

Figure 11. Equivalent von Mises stress for the section 350 mm with grooves at 1.2 ms

To compare the analytical with the simulation results, the equivalent analytical stress is calculated by the von Mises formula [6]:

$$\sigma_e = \sqrt{\sigma_h^2 + \sigma_r^2 - \sigma_h \sigma_r} \quad (1)$$

Where σ_h is the hoop stress and σ_r is the radial stress.

Figures 12 and 13 represents the plots of the equivalent von Mises stress distribution obtained from the 2D simulations for the sections (with and without grooves) compared with the calculated analytical results.

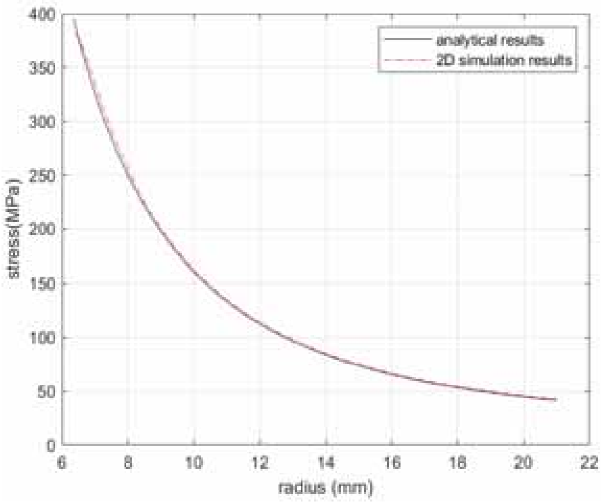

Figure 12. Analytical and numerical equivalent von Mises stress for the section 100 mm at 0.5 ms

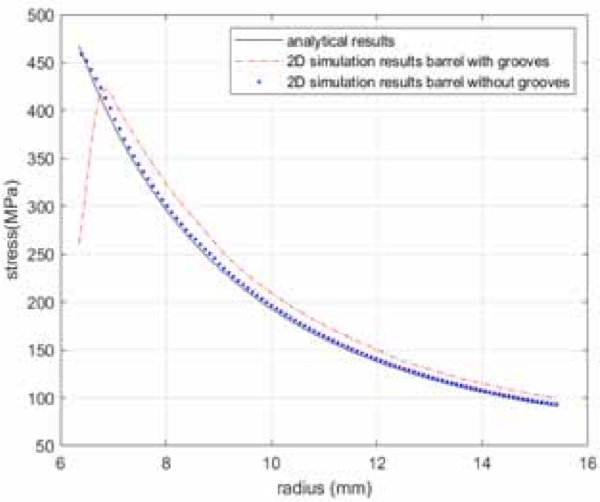

Figure 13. Analytical and numerical equivalent von Mises stress for the section 350 mm (with and without grooves) at 1.2 ms

Figures 14 to 17 represent the visualization of the equivalent von Mises stress distribution obtained from the 3D simulations for the CAD models (with and without grooves). While Figure 18 and 19 represent the plots of the equivalent von Mises stress distribution obtained from the 3D simulations at the specified sections compared with the calculated analytical results.

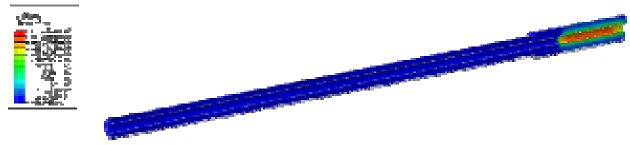

Figure 14. Equivalent von Mises stress for the 3D barrel without grooves at 0.5 ms

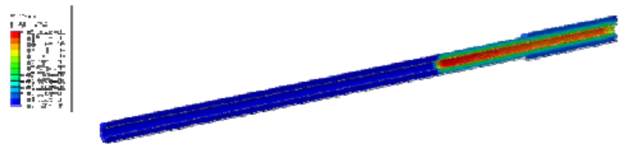

Figure 15. Equivalent von Mises stress for the 3D barrel without grooves at 1.2 ms

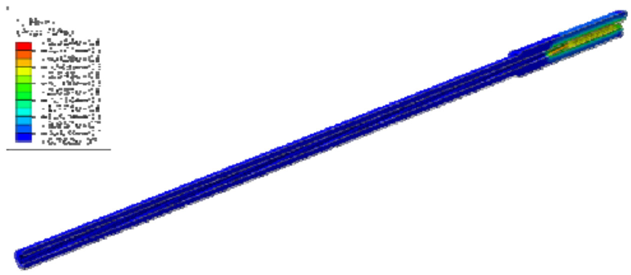

Figure 16. Equivalent von Mises stress for the 3D barrel with grooves at 0.5 ms

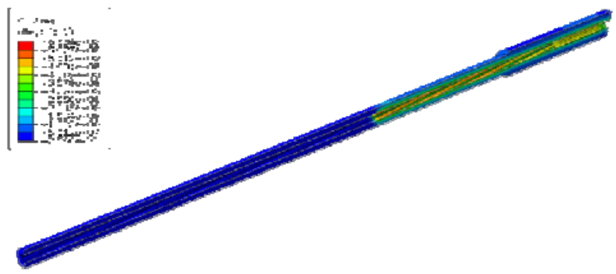

Figure 17. Equivalent von Mises stress for the 3D barrel with grooves at 0.5 ms

The results of the 2D (sections without grooves) and 3D (barrel without grooves) simulations match exactly the analytical calculations of the equivalent von Mises stress in the sections 100 mm and 350 mm at 0.5 ms and 1.2 ms respectively. The satisfactory agreements between those results increase the credibility of this work and allows us to assume that the equivalent von Mises stress obtained from the 3D simulations for the barrel with grooves correspond to the real equivalent stresses.

The existence of grooves affect the distribution of the equivalent von Mises stresses over the sections of the barrel. Fig.11 shows that the highest stresses are located in the grooves of the barrel, specifically in the close regions to the lands. This is explained by the creation of stress concentrations.

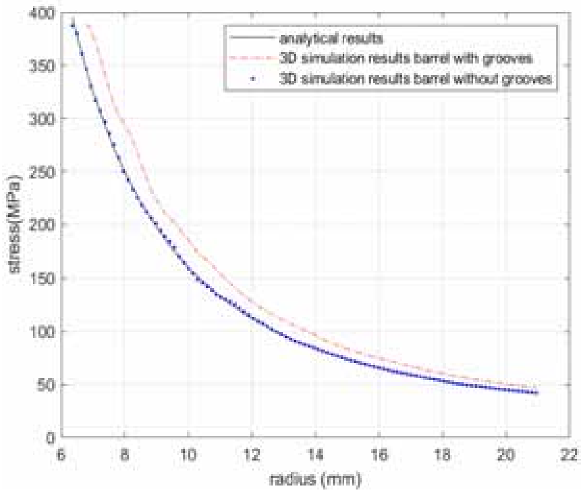

Figure 18. Analytical and numerical equivalent von Mises stress for the section 100 mm (with and without grooves) at 0.5 ms

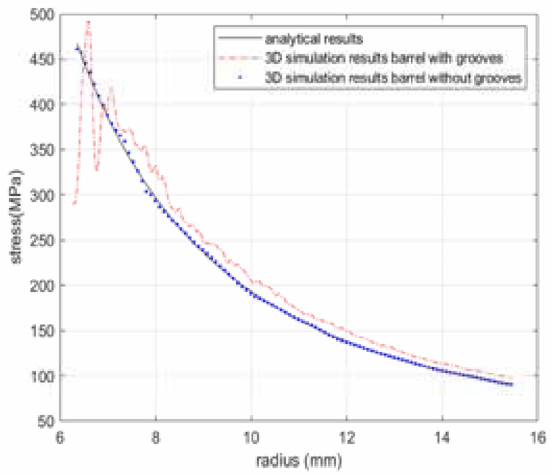

Figure 19. Analytical and numerical equivalent von Mises stress for the section 350 mm (with and without grooves) at 1.2 ms

Fig.13 shows that the results of the 2D simulation of the section 350 mm with grooves are greater than the analytical calculations for the values of radii greater than 6.9 mm. This is due to the fact that the diameter of grooves is larger than the diameter used to perform the analytical computations of the equivalent von Mises stress.

The diameter of the combustion chamber in the 3D CAD model with grooves is 6.86 mm. As a consequence the values of stress in the 100 mm section at time 0.5 ms are greater than the analytical values as shown in .8.

Fig.19 shows that the plot of results from the 3D simulation for the section 350 mm at 1.2 ms is quite different than the one obtained from the 2D simulations. The maximum equivalent stress obtained by the numerical 3D simulation is 491.52 MPa at the radius 6.6 mm, while the maximum equivalent stress obtained by the analytical calculations is 467.41 MPa for the 6.4 mm radius. The graph shows fluctuations in the stresses values. Stress concentrations in the regions between grooves and lands implicate the augmentation in the equivalent stress for the associated radius. The application of pressures on the grooves side walls generate other types of stresses like the axial stress and torsional stress. The mentioned stresses are the main cause for the creation of the shown fluctuations in the stresses values.

Conclusion

The stress response of the 12.7 mm barrel was investigated in the present work. The loads applied on the interior surfaces of the barrel are the pressures of the burned propellant obtained by the tow phase flow numerical calculations. The analytical radial and hoop stress were calculated using the lame equations for the stresses in the thick walled cylinders. The simulations were performed to determine the equivalent stress in the barrel sections.

The compatibility between the analytical and numerical results is satisfactory.

The 3D simulation on the barrel with grooves shows that the applied pressures on the side walls of grooves affect the response of the barrel. It also shows that the stress concentration is important in the regions between the grooves and lands. Using 3D simulation can help to get more precise safety factors of the barrel thicknesses when designing a new gun.

For more realistic picture of the barrel stress responses, it should be taken into account the influences of the neglected loads. As the friction forces and interactions between the projectile and the barrel, the influence of temperature and the presence of the bullet cartridge in the combustion chamber.

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Received: 15.07.2020.
Accepted: 01.09.2020.

Uticaj unutrašnjeg balističkog pritiska na naprezanje cevi puške

U radu je prezentovano naprezanje cevi puške 12,7 mm, pod uticajem pritiska barutnih gasova. Tokom procesa opaljenja, cev oružja (puške) se nalazi pod uticajem različitih mehaničkih, hemijskih i toplotnih opterećenja. Mehanička naprezanja usled pritiska barutnih gasova su najveća po intenzitetu i ona su razmatrana u ovom istraživanju, dok su svi ostali uticaji zanemareni. Profil promene pritiska je dobijen na osnovu unutrašnje balističkog matematičkog modela. Za proračun naprezanja cevi primenjene su Lameove jednačine za slučaj opterećenja debelozidnih cevi. Analizirana su opterećenja na određenim presecima cevi u diskretnim vremenskim intervalima. Za numeričke simulacije korišćena su dva modela cevi (sa i bez unutrašnjih žlebova). Poređenje dobijenih rezultata proračuna naprezanja za oba modela cevi pokazali su dobra poklapanja analitičkih i numeričkih metoda.

Ključne reči: **naprezanje cevi, unutrašnja balistika, Lameove jednačine.**