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Investigation of Mechanical Behavior of Barrel after Geometric Changes on the Mortar

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ABSTRACT

The area close to the firing part as of the muzzle of a 120 mm mortar consists of trapezoidal threads. In order for the 120 mm mortar to hit the target, the target is aimed by giving the required angle with the help of these trapezoidal screw threads. Since it takes a lot of time to set the target in this way, the aim is to develop a hydraulic mechanism that automatically gives an angle to the system by lifting the trapezoidal screw threads instead of mechanically setting the angle to be adjusted easily in the shortest time. Thus, it is intended to convert the mortar into a full-automatic system that can rotate 360° around itself and can be adjusted to the desired angle in a short time and very precisely. The present study is conducted in two steps. At first, thermo-mechanical analyses for the stresses affecting during firing of the currently used 120 mm mortar with a screw thread were investigated by ANSYS Workbench finite elements method. Then, the status of the mortar after removing the screw threads was examined in the ANSYS Workbench program under the effect of the same stresses and the results were compared between the two mortars and it was examined whether it is safe to remove the screw threads. When the analyses were examined, the temperature distribution was higher in the barrel without screw threads as a result of the first thermal analysis. When the analyses were examined in terms of statics, it was observed that it was high in the mortar barrel without screw threads

Keywords: Mortar; Mortar barrel; Barrel; Interior ballistic

1. INTRODUCTION

The 120 mm mortar, which has an important role in the defense industry, covers the largest firearm class in its field and is present in the inventory of all Armed Forces. The area close to the firing part as of the muzzle of a 120 mm mortar consists of trapezoidal threads. For firing a 120 mm mortar, ammunition is manually loaded from the muzzle and is shot one by one. Therefore, the 120 mm mortar is not fired directly at the target, but instead, it drops the target from the air after giving a certain angle. The ammunition coming out of the barrel is not aimed directly at the target, it can be defined as it first rises and then suddenly falls on the target from above. In this way, it has the ability to shoot with extreme frequencies behind hills or tall buildings. The mortars are used with a range of minimum 1500 m and maximum 8000 m. The design of a mortar with such a range is quite important. Fig. 1(a) shows the 120 mm mortar used today and Fig. 1(b) shows the ammunition of the mortar. This is the first study conducted on the removal of screw threads that are present on a 120 mm mortar. Previous studies have generally focused on interior ballast and combustion chambers. The studies conducted on the barrel are as follows. In the study of Esen and Koc, dynamic behaviors of an antiaircraft barrel with a diameter of 35 mm and a length of 3240 mm were investigated. In the study, the cartridge bullet is restricted with the dynamic interaction of the barrel by excluding the shock waves occurred at the time of denotation. Ozcan, examined the strength status of a sawn-off firearm depending on the interior ballistic[3]. It is intended to make the design of an optimal barrel by performing the strength analyses of the gun tube having a polymer structure with a caliper of 9 mm, a barrel length of 86 mm, and six grooves via finite elements method. In the study of Huang, a 105 mm mortar barrel was modeled and damage analysis for the barrel due to denotation was conducted by using the volume energy density method and finite elements analysis[4].Ozturk, investigated the effects of the barrel design on back-blast via computational fluid dynamics method by using the ANSYS Fluent program[5]. In the study of Tawfik, the stability of the Euler-Bernoulli rod of the effect of a moving bullet was revealed by using the eigenvalue method of the finite elements model[6].

Sonmez, discussed the mathematical modeling and analysis of the stresses that occur during firing in the combustion chamber of a howitzer barrel[7]. A mathematical model of the stresses affecting the barrel combustion chamber, where the maximum stress in the barrel during firing is present, was obtained. In the study of Deng *et al.*, the behaviors of the barrel under the pressure developed inside were investigated by using the- nonlinear discontinuous finite elements method after a 5.56 mm caliber bullet is fired. Vallier-Heydenreich method was used to formulate the barrel pressure and to make an input. In addition, the velocity of the bullet at the muzzle

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was compared with experimental data and consistent results were obtained. They stated that the simulation in their study can save time in the further research regarding the barrel design[8]. Ozguder, issued a study considering the interior ballistic behaviors of a M101 mortar barrel[9]. The primary goal of the present study is to choose a material instead of the M101 mortar barrel due to its weight and to have the mortar alleviated. In the study, the weight of the mortar was lightened, post-firing tensile strengths were examined by the iterations via ANSYS in order to determine whether it is safe or not. Babaei, discussed the M24 gun tube in his study. After the gun is fired, the deformations to be caused at the barrel due to the pressure were examined. Stress analyses was conducted by the help of ANSYS by entering the radial force value occurred in the area where the denotation occurred[10]. After the study, it was determined that the material selected in the study passed the yield point and a serious deformation occurred in the area where the denotation occurred. In the study of Xavier, the flow of a bullet after firing was examined by using ANSYS CFD computational fluid mechanics[11]. As a result of the study, it was observed that the bullet to be fired after itself affects the target direction and the post-firing flow is very strong. Besides, Isik, determined a parametric modeling and conducted a study on modeling the velocity distribution, bore pressure distribution, temperature level, and heat transfer amount parametrically[12]. Lagrangian approach was used for the effective pressure and the pressure distribution inside the barrel was found via the obtained formula. In the study of Senturk, the calculation of the pressure and temperature values affecting the barrel with known dimensions was conducted[13]. In his study, ANSYS finite elements program as used and thermomechanical stress analysis of the barrel in burst mode was conducted by using the values in question. Gungor, studied on a metal matrix wrapped barrel instead of a barrel made of high-strength steel[14]. Within this scope, internal pressure was primarily applied to the steel barrel chamber, and its strength and structural analysis were examined. Then, the isotropic metal matrix composite was assembled on the barrel via the shrink fit method, and the optimisation was made to determine the diameter that will capture the strength values of the barrel produced from steel. Akbulut, conducted a study regarding the realisation of the heat transfer from the gases produced by the combustion of the propellant charge to the interior wall of the artillery barrel when bursts are fired[15]. As a result of this study, it was concluded that the naturally cooled barrel is insufficient for multiple firing. In the study of Buyukcivelek, control and analysis of the gun tube vibrations were done and according to the result obtained, muzzle displacements were checked by the existing weapon stabilisation systems[16]. Gegaregian and Costa studied a mortar design for light weapon systems by observing the light weapon systems[17]. Swab and Wereszczak conducted a study on the thermal and mechanical properties of advanced ceramics for gun barrel applications. They used the modeling and designs of the new program for further evaluation and to determine the best gun tube designs[18]. Yohannes Asfaw conducted a study on the design and production of a mortar shell[22].

In our study, unlike other studies, stress analyses were made by making geometrical changes. This study was carried out on a 120 mm trapezium screw threaded mortar barrel that is used as a standard in the defense industry. In the present study, the trapezoidal screw condition of the currently used standard barrel and the situation after removing the trapezoidal screw threads were examined from all aspects. These analyses were conducted in two steps. At first, thermo-mechanical analyses for the stresses affecting during firing of the currently used 120 mm mortar with a screw thread were investigated by ANSYS Workbench finite elements method.

2. MODELING AND ANALYZING MORTAR

2.1 Acceptances in Analysis Solution

While developing a finite elements model, the system is simplified by making some assumptions and a solution is made accordingly. However, such simplifications reduce the analysis period of the program and also ensures that the outputs are as

Fig. 1 (a) Currently used screwed 120 mm mortar[19] (b) 120 mm mortar ammunition[21].

close to the real results as possible.

These assumptions can be listed as follows:

- Model effects of the barrel are neglected (It is foreseen that the weapon will not make any bursts)
- After the bullet leaves the barrel, some gas remains inside and these gases cause pressure. However, this pressure is not considered in the strength calculations due to the reason that it is quite smaller than the pressure at the time of burst
- Close side of the barrel to the cam is referenced as "0"
- It is assumed that the denotation effect has caused a linear pressure effect at the target and does not cause any deformation in the material
- While considering the yield strength of the barrel, the autofrettage effect is neglected
- The heat transfer throughout the barrel length is accepted as linear.

2.2 Model Formation

Before the mortar barrel is analysed at ANSYS program, two different barrel models are developed in SolidWorks3B modeling program by the knowledge of technical drawing and these two barrels will be compared. Internal diameter of the is 119.9 mm, outer diameter is 160 mm, the barrel length is 1900 mm, and the wall thickness is 40 mm. Figure 3 shows the technical drawing of the 120 mm mortar barrel and its screw threads. Fig. 5. The comparison considering the technical drawing in SolidWorks 3B program, the current mortar barrel model given in Fig. 3 is developed. Figure. 3 shows the model of ammunition-loaded mortar barrel. Solutions were made by taking meshing, nodes 217762 and elements 125062.

The barrel to be used in analyses is 120 mm and this is also the inner diameter of the barrel where the bullet proceeds. High pressure occurs via the combustion of the gas in the barrel combustion chamber, and thus, the bullet proceeds in the barrel. The area where the propellant charge starts to burn is called as the combustion chamber. Since the greatest pressure in the barrel occurs in this part, the barrel combustion chambers are specified as the most critical points in the barrel design. In addition, as a result of firing the barrel, flareback force occurs at the time the bullet leaves the barrel. Due to this reason, the strength affecting the barrel and resulting deformations are examined in the present study. In the study, thermo-mechanical analysis is performed that has occurred in the mortar to be examined. The main purpose here is to investigate and compare the firing of the barrel when the screw threads in the barrel are removed and thermo-mechanical effects that may occur in the barrel.

2.3 Energy Values in the Barrel

Upon examining the results of the literature review, it is seen that such studies have mainly focused on the energy distribution in the barrel. Therefore, necessary calculations for the analyses were made over these ratios and the results were evaluated accordingly by considering such studies as a reference. As a result of the literature review, kinetic energy was calculated by accepting the initial velocity of the bullet stated by MKE (Machinery and Chemical Industry Institution) as 365 m/s and its weight as 18 kg. The ratio of the energy transferred to the barrel to the total energy was taken as 23%.

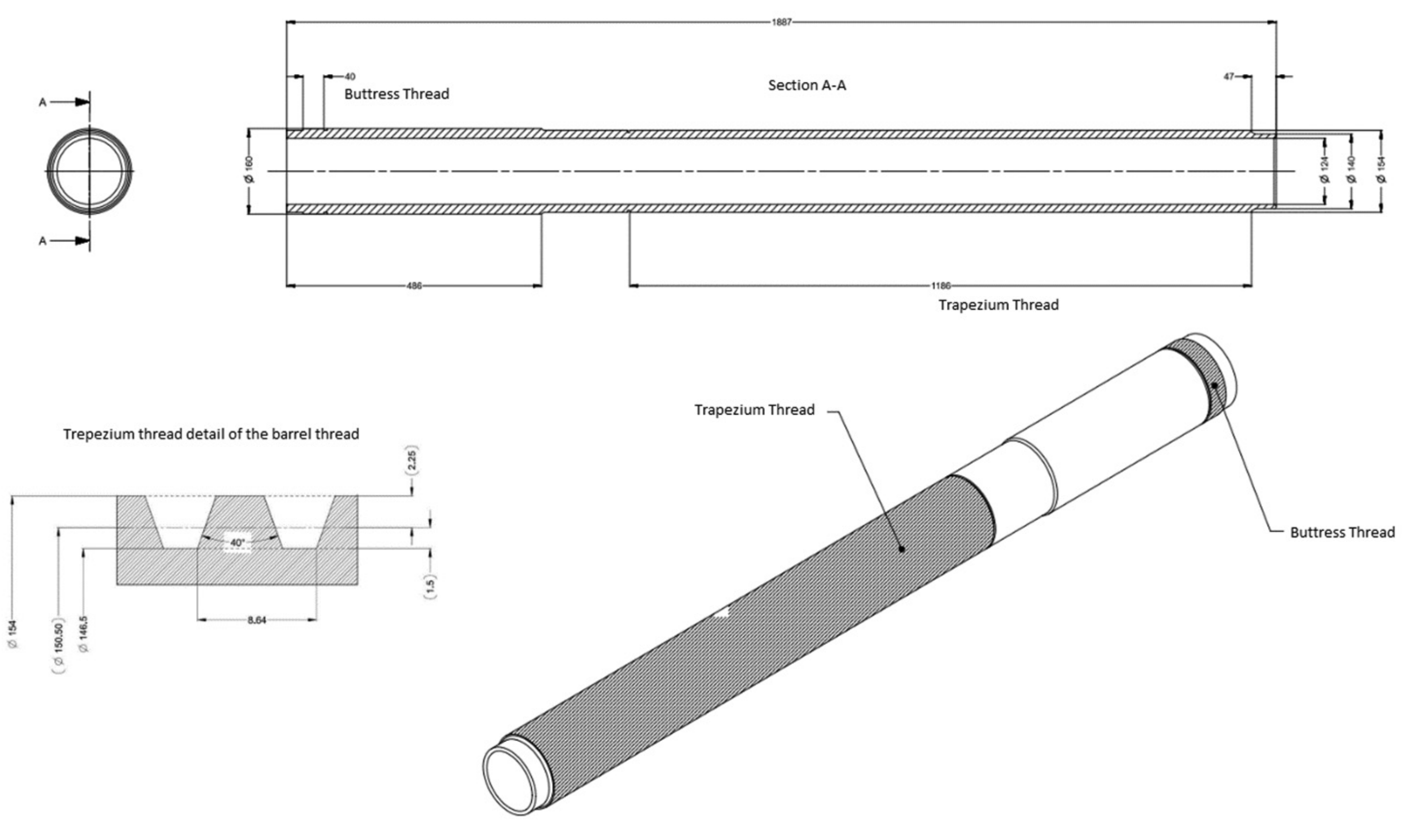

Figure 2. Technical drawing of a trapezium screwed 120 mm mortar.

Table 1. Internal ballistic energy distribution[14]

Energy in the barrel	Percentage
Return of the Bullet Core	0.2
Friction Inside the Barrel	3
Movement of Gases in the Barrel	3
Flareback	0.1
Barrel and Bucket Heating	21
Heating of Gases	42

(Table 1). This energy was approximately 920 kJ. Table 2 shows the energy values found as a result of the calculations. These values were used as input for thermal analysis in ANSYS program.

As a result of the literature research, the initial velocity (365 m/sec) and weight (18 kg) of the bullet stated by MKE (Institute of Mechanical Chemistry) and the kinetic energy were calculated with Equation (3.46). The amount of heat transferred to the barrel thermally was calculated from the distribution percentages given in the tables. The ratio of the energy transferred to the barrel to the total energy was taken as 23%. This energy is about 920 kJ.

For the thermal load calculation, first the amount of kinetic energy is calculated[14]. All solutions were calculated as W and analysed. If the amount of thermal energy in Joule is converted into Watt.

$$KE = \frac{1}{2} m v^2$$

$$\frac{1}{2} \text{X } 18 \text{ X } 365^2 = 1199025 \text{ J}$$

Mass is the ammunition weight and velocity is the initial velocity of the ammunition. If this amount of kinetic energy is distributed according to the energy ratios released in the barrel and the ratio-proportionality is established with the values, the amount of thermal energy is calculated as approximately

Table 2. Energy distribution in 120 mm mortar barrel

Type of energy	Energy amout (%)	J (Nm)
Kinetic energy	30	1199025.0
Waste energy	29	1159057.5
Thermal energy	23	919252.5
Gas energy	15	599512.5
Loss energy	3	119902.5
Total	100	3996750.0

920000 J. Energy distribution inside the barrel[22].

In the literature search, pressure-time graph is generally expressed by the situation given in Fig. 3. In the present study, this graph is taken as a basis for the pressure-time situation. Pressure-time graphs also show the reaction time. Reaction time is the period elapsed for thermal transmission. This period is taken as 15 ms in the study. This period may vary according to the type of the gunpowder and ambient conditions. It is assumed that the thermal energy is transmitted to the system

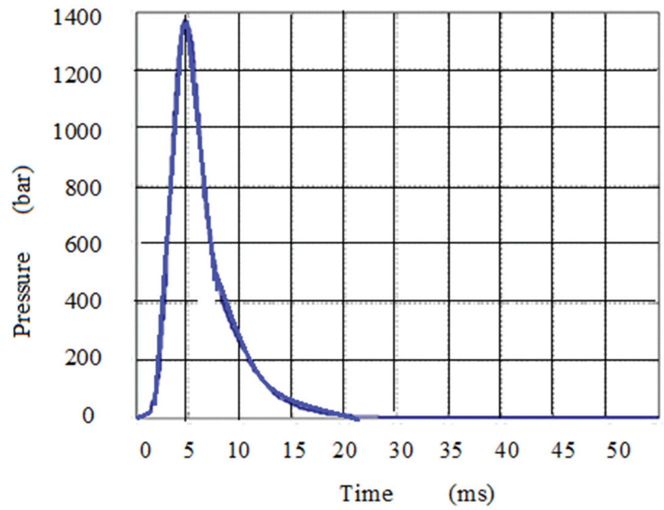

Figure 3. Time for the ammunition to leave the barrel[22].

during this time (denotation period).

2.4 Meshing the Mortar Barrel

Meshing was performed on the barrel after the model drawn in the SolidWorks program was transferred to ANSYS for analysis. This process is quite important when it is considered that the strong effect on the analysis results is caused by the meshing process. Meshing process of trapezium threaded mortar has two steps. At first, the barrel of the mortar was meshed, and then, screw threads were meshed, and finally, both parts were combined. Figure 4 shows the meshing process on the surface of the screw threaded mortar barrel. Directly proportional energy distribution was made from the blast chamber to the muzzle.

2.5 Stress Values and Material Properties Obtained as a Result of Combustion in a Mortar

The greatest pressure in the barrel occurs in the combustion chamber where firing starts. In fact, combustion is a time-dependent denotation situation. This value is measured as less than 3.10^5 N in a 120 mm mortar[21]. In the analyses conducted in the present study, M209 propellant charge with the highest denotation value and 32CrMoV1210 steel as the material were used[17]. Barrel material 32CrMoV12-10 alloy (Ovako 398Q) is an ingot cast high tensile quench and tempering steel with high hardenability. The grade has high strength and toughness. The strong carbide and nitride formers makes it very well suited for nitriding. The grade is produced with the quality class IQ (isotropic quality). This ensures a very low number of elongated sulphide inclusions which will give more isotropic properties. Figure 6 shows the general mechanical properties of the barrel material[23].

2.6 Thermo-Mechanical Analysis via ANSYS Finite Elements Method

Within the scope of the current study, since a thermo-mechanical analysis will be conducted, the amount of energy transferred to the barrel and the time this energy is applied are entered. This effect should be reflected as the heat flow in the ANSYS thermo-mechanical analysis. The heat flow was calculated as 61.3 MW when thermal energy was taken

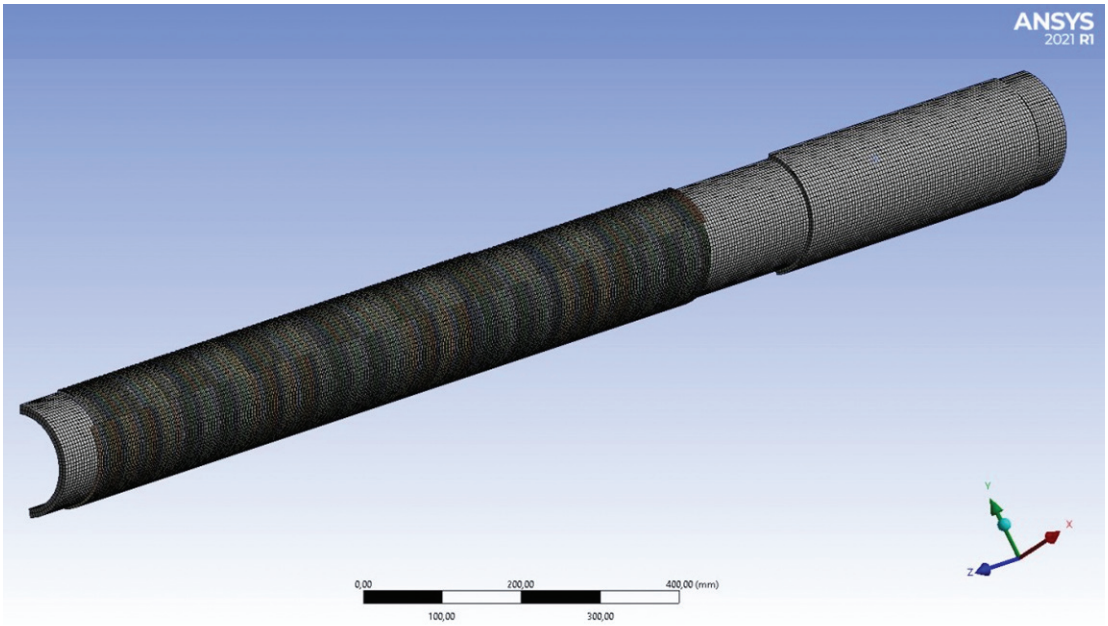

Figure 4. Meshing process of the screw threaded mortar.

Cast	Weldability		C %	Si %	Mn %	P %	S %	Cr %	Ni %
IC	CEV 1.48$_{max}$	Min	0.30	0.20	0.40	-	-	2.80	-
	Pcm 0.71$_{max}$	Max	0.35	0.35	0.60	0.015	0.001	3.30	0.30

Youngs module (GPa)	Poisson´s ratio (-)	Shear module (GPa)
210	0.3	80

Yield strength min [MPa]	Tensile strength [MPa]	Reduction of area Z_{min} [%]	Hardness
800*	940 typical	70	300 HB typical

Figure 5. Chemical composition and mechanical properties of 32CrMoV1210 material[23].

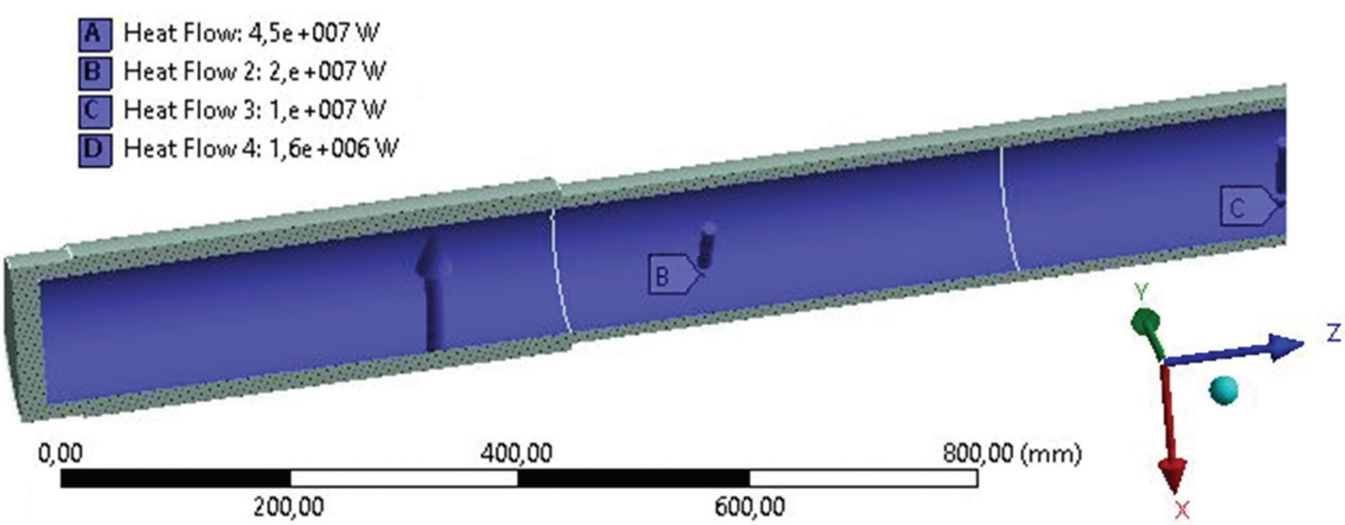

Figure 6. Heat flow distribution throughout the barrel.

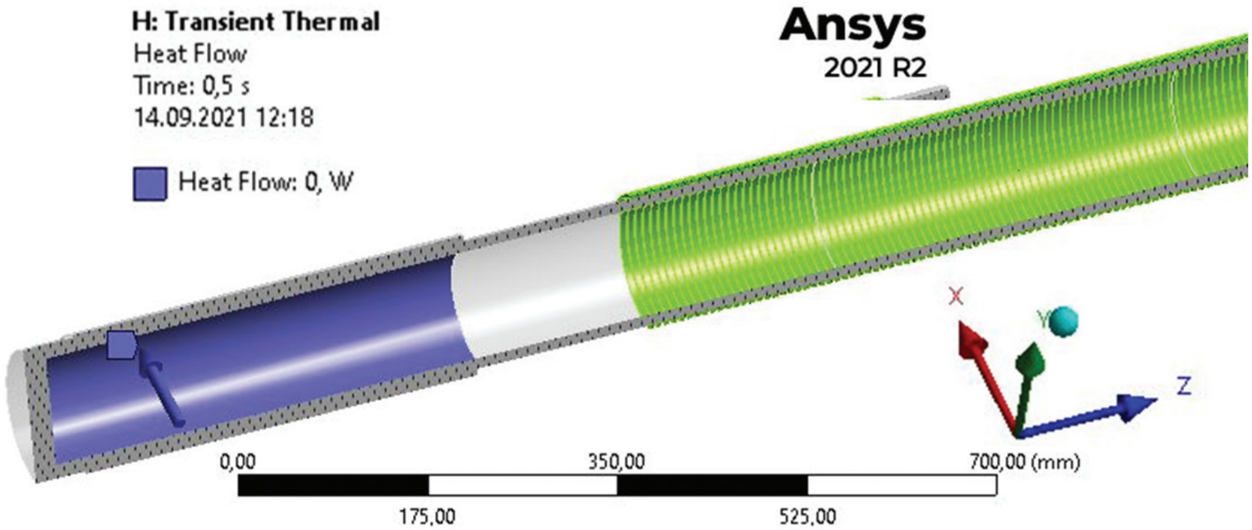

Figure 7. First zone heat flow distribution of screw threaded mortar barrel.

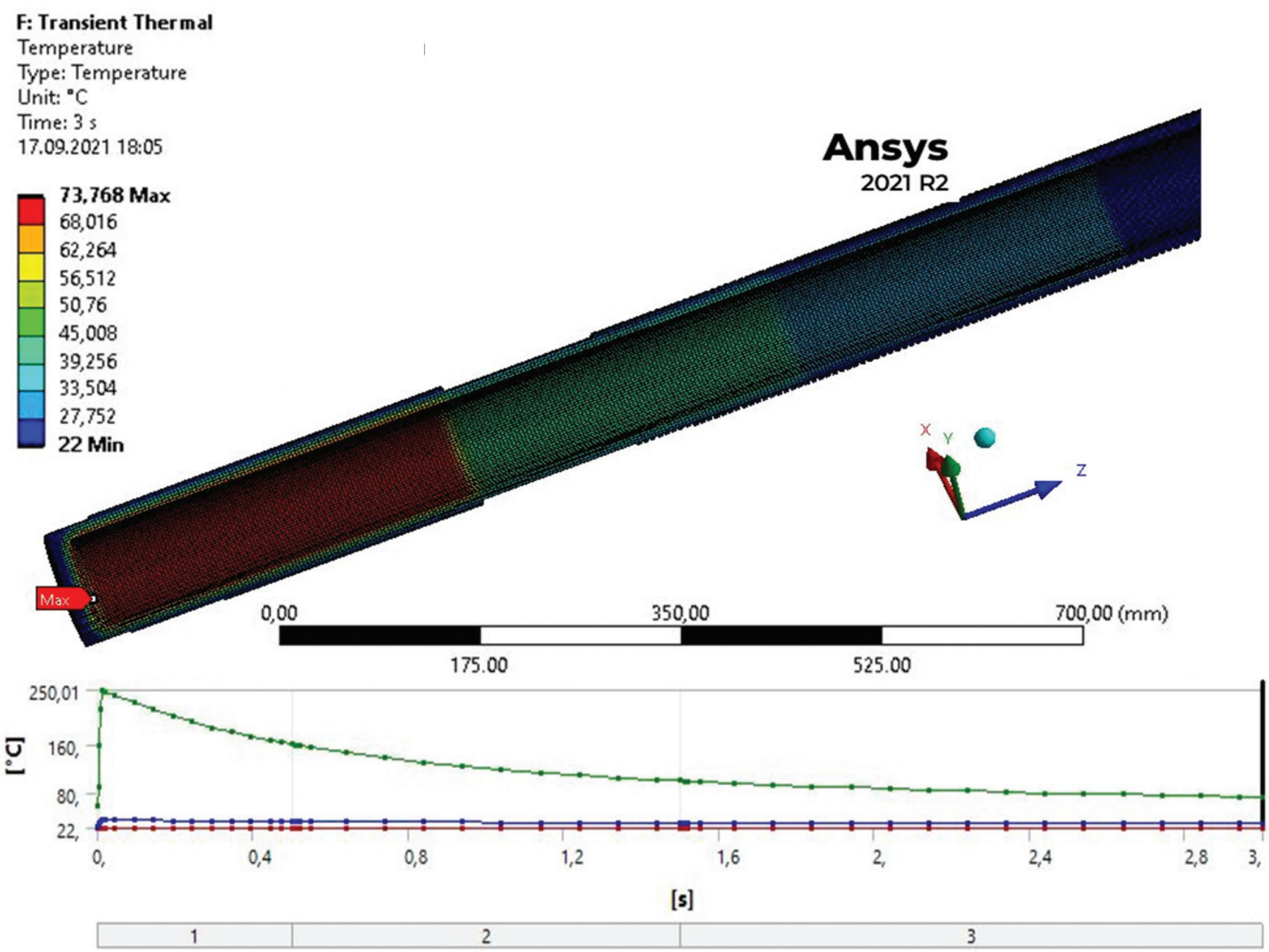

Figure 8. Temperature distribution occurred in the screw threaded mortar.

as 920 kJ and time as 15 ms given in Table 1. Heat transfer in the thermal factor is realised throughout the barrel. In Fig. 6, the heat flow value of 61.3 MW is distributed in a linear decrease effect by creating certain surfaces on the inner surface of the barrel. This distribution can be made more uniform by using the experimental data. When experimental data are applied, the temperature distribution differences in threaded and blank designs will change. The reason of the difference in the temperature values read from the analysis results is that the heat flow distribution is assumed to be linear. Ammunition design is also taken as a basis during the distribution process. The ambient temperature value is given to the blank part at the muzzle seen in the figure. Ambient temperature is accepted as 22 °C. For the first zone (Explosion Zone).

$$P = \frac{E}{t}$$

The amount of power released as thermal energy.

$P = \frac{920000}{0.015} \tilde{=} 61.3MW$ is calculated as.

In this study, since a thermo-mechanical analysis will be made, the amount of energy transferred to the barrel and the time this energy is applied are given. This effect should be reflected in the ANSYS thermo-mechanical analysis heat flow. Joule and heat flow conversion formula are given. When the thermal energy given is 920 kJ and the time is taken as 15 ms, the calculated heat flow is calculated as 61.3 MW. In the thermal effect, heat transfer takes place along the barrel. Since there is no thermal distribution plot across the barrel, a linear decrease is assumed. The heat flow value of 61.3 MW is distributed in a linear decreasing effect by creating certain surfaces on the barrel inner surface. This distribution can be made more uniform with experimental data. When experimental data are applied, the temperature distribution differences in threaded and threadless designs will change. The reason for the difference in the temperature values read from the analysis results is that the heat flow distribution is assumed to be linear. Ammunition design was also taken as a basis during the distribution process. The ambient temperature value is given to the empty part at the tip of the barrel seen in the image. The ambient temperature is assumed to be 22 °C.

As seen in Fig. 7, some energy amount was applied to the combustion chamber (1st Zone), 3.10^7 W. This value is the energy amount released during denotation. Due to the fact that the barrel is divided in four equal parts, the energy amount affecting the second part was found as 2.10^7 W. This value was used as an input for the analyses of the screw threaded mortar barrel and the mortar with removed screw thread. The energy amount affecting the third part of the barrel was found as W. This value was used as an input for the screw threaded mortar barrel and the mortar with removed screw thread. Figure 6 shows the third zone of the screw threaded mortar. The energy amount affecting the fourth part of the barrel was calculated as W. This value was used as an input for the analysis of the screw threaded mortar barrel and the mortar with removed screw thread. As a result of the analysis made by entering these values, when the graph is examined, it is seen that the maximum temperature value is 250 °C in the screw threaded mortar shell in Fig. 9, and 496.14 °C in the blank barrel design in Fig. 9. The difference between is related to the linear use of heat flow distribution. As explained in the previous sections, it is a fact that more accurate results will be obtained if the heat flow distribution is used by obtaining experimental data.

It was observed that there is a temperature difference when comparing the screw threaded mortar barrel and the blank mortar barrel. This occurs as a result of the linear distribution. Since the analysis is time dependent, temperature difference may be seen at the beginning of iteration. However, it is seen that this situation does not occur in the subsequent iterations of the analysis. In the time-dependent analysis, analysis settings such as time-step and heat flow distribution may cause this situation. When the mortar is examined in terms of the total heat flux amount, maximum value was observed as 0.0827 W/mm^2 and minimum value as 4.414×10^{-17} W/mm^2. The results obtained were calculated as maximum 0.062 W/mm^2 and minimum $2.165.10^{-17}$ W/mm^2. While transferring the thermal analysis data to the structural analysis, the situation was used as the fixation point of UZ=0, UY=0, UX=0 for the barrel. The pressure effect resulting from the detonation was applied to the inner surface of the barrel in the combustion

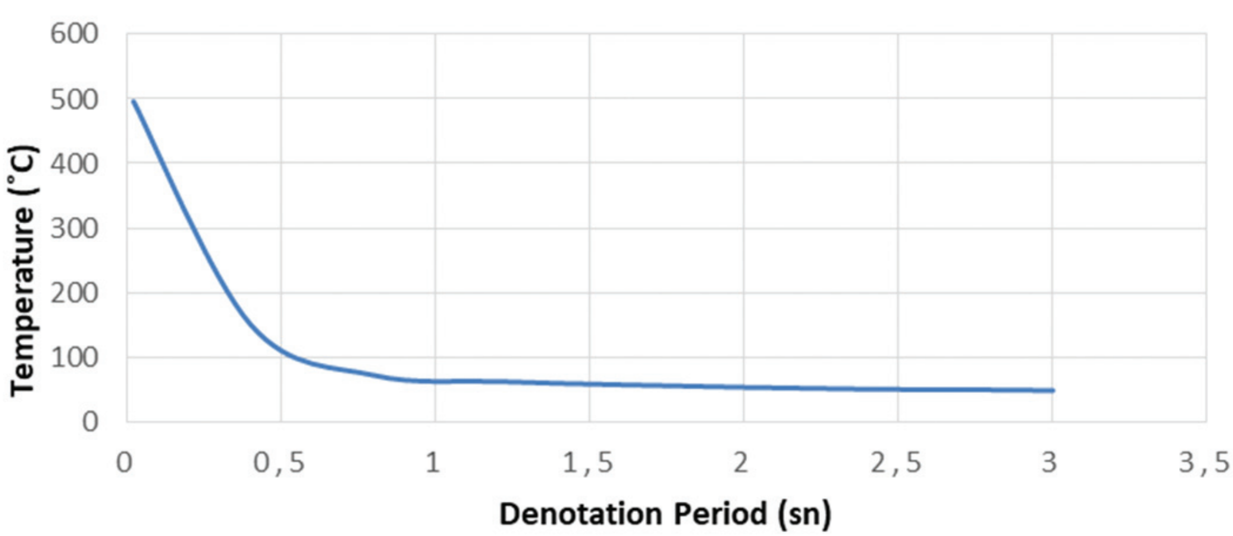

Figure 9. Temperature-time distribution graph occurred in the mortar with no screw thread.

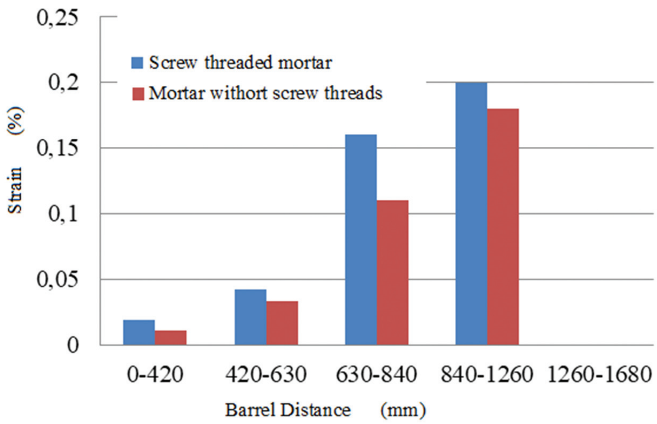

Figure 10. Comparison of total deformation amount.

first, thermo-mechanical analyses for the stresses affecting during firing of the currently used 120 mm mortar with a screw thread were investigated by ANSYS Workbench finite elements method. Then, the same stresses for the state of the mortar during firing after the screw threads on the mortar are removed, the results are examined in the ANSYS Workbench program, and the necessary comments are explained as follows.

As a result of the thermal analysis conducted on the screw threaded mortar barrel and the mortar barrel without screw threads, different values were obtained in terms of temperature in both barrels. Maximum temperature value obtained in the barrel of the screw threaded mortar was found as 250 °C. This value was found as maximum 496.14 °C in the mortar barrel without screw threads. The reason for this increase is that the temperature value is found as low since the screw system acts

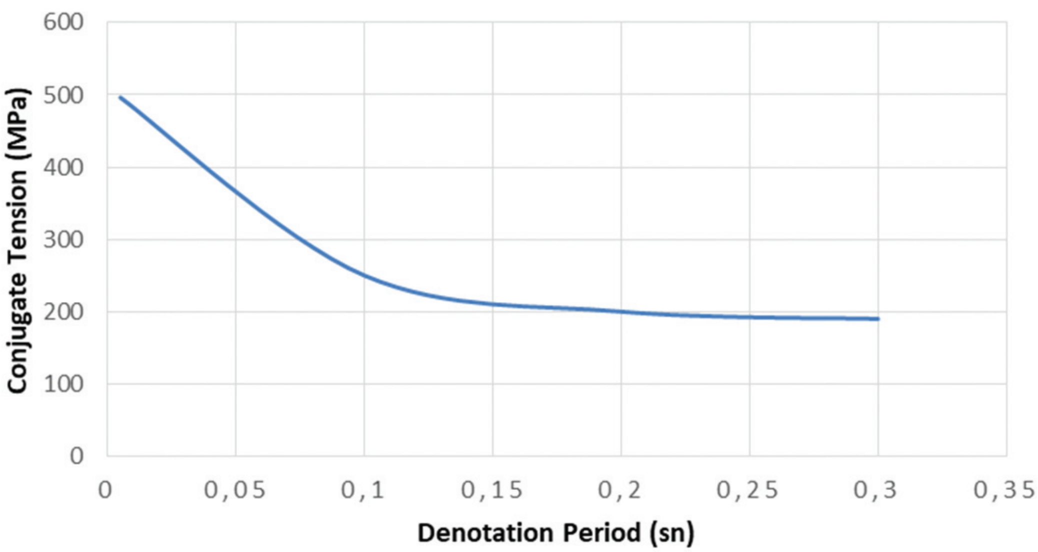

Figure 11. Graph of the conjugate tension-time distribution occurred in the screw threaded mortar barrel.

zone (zone 1), reaching the maximum value in 5 ms and the minimum value after 15 ms, where the pressure given in the pressure time graph in Fig. 3 was affected. As the analysis period, 3 sec, used in the thermal analysis, was entered. As a result of the structural analysis, the Von-Mises stresses, strain ratio values and total deformations of two different designs with screw thread and without screw thread are given. As can be seen in Fig. 10, the deformation distribution of the thermo-mechanical analysis result of the screw threaded mortar is 0.2089 mm. Total deformation was obtained along the barrel.

It is seen that the total amount of conjugate strain rate occurring in the screw threaded mortar barrel is 0.002371. Total conjugate strain rate is found as 0.004285 when the screw threads are removed. Graph distribution is given in Fig. 11.

3. CONCLUSIONS

A study was carried out on a 120 mm trapezium screw threaded mortar barrel that is used as a standard in the defense industry. In the present study, the trapezoidal screw condition of the currently used standard barrel and the situation after removing the trapezoidal screw threads were examined from all aspects. These analyses were conducted in two steps. At

as a cooling fin in the screw threaded mortar. In addition, when the screw threads are removed, cooling cannot be performed completely, thus the temperature value in the barrel is found to be high. However, this temperature is not permanent in a mortar and does not cause permanent damage to the barrel since it is cooled very quickly as seen in the tension results.

When the total heat fluxes are considered, total flux of the screw threaded mortar barrel was obtained as 0.062 W/mm^2. This value was maximum 0.082W/mm^2 in the mortar barrel without screw threads. The reason for this situation can be explained as follows. After the screw threads are removed, the heat flux is found as high due to the reason that the amount of heat is higher in the barrel, and it is longer lasting than the screw threaded mortar.

As a result of the examination of the static analysis parts of the screw threaded mortar barrel and the mortar barrel without screw threads under thermal loads, the total amount of deformation occurred in the screw threaded mortar barrel was obtained as 0.2089 mm in terms of total deformation. This value was found as maximum 0.1851 mm in the mortar barrel without screw threads. As the same, the following explanation can be done for this result. After the screw threads on the mortar are removed, the amount of deformation was found to be higher due to the reason that the amount of temperature would be higher in the barrel, and it was also longer lasting than the screw threaded mortar.

The value for the total strain rate was found to be 0.002371 in the screw threaded mortar barrel and 0.004285 in the mortar barrel without screw threads. The above-mentioned cause and effect relationship can be specified for these result values.

When Von-Mises stresses are examined, it was calculated as 496.35 MPa in the screw threaded mortar barrel. This value was found as maximum 681.31 MPa in the mortar barrel without screw threads. Babaei, in his study, after the gun is fired, the deformations to be caused at the barrel due to the pressure were examined. Stress analyses was conducted by the help of ANSYS by entering the radial force value occurred in the area where the denotation occurred[10]. As can be seen, our results are supported by the literature.

Below mentioned explanation can be done for Von-Mises tension result values. Since the outer diameter of the screw threaded mortar barrel is larger than the diameter obtained after removing the screw threads from the mortar, the stress value is high. In other words, Von-Mises values were higher in the mortar barrels without screw threads due to the decrease in the wall thickness of the barrel. Since the yield strength of the material of the mortar barrel is 900 MPa, it can be seen from the analysis results that the results for both the screw threaded barrels and barrels without screw threads are safe and that there will be no harm for use in this way. The values of these results obtained in the study are only the results obtained for the Thermo-Mechanical analysis. Since the temperature increase in the barrel after firing is inevitable in all ballistic weapons, it will affect all the stress and calculations to be occurred.

Therefore, only Thermo-Mechanical analysis was performed, and mechanical strength calculations were made according to the results.

By using the ANSYS finite element program used in Şentürk's study and the mentioned values, thermomechanical stress analysis of the barrel in burst mode was performed. As can be seen, our results are supported by the literature.

As a result, when analyses were examined, the temperature distribution was higher in the barrel without screw threads as a result of the first thermal analysis. When analyses were examined in terms of statics, it was observed that it was high in the mortar barrel without screw threads. The reason is that the trapezoidal screw threads in the screw threaded mortar act as a flap in the barrel, that is, it also performs the cooling process. In this regard, since it provides a better heat transfer in the barrel, the temperature distribution is higher than that of the mortar barrel without screw threads. Since the temperature distribution is higher in the mortar without screw threads, the results of the static analysis performed in the screw threaded mortar barrel are higher. When all these results are examined and these results are compared with the studies previously conducted in the literature, it is observed that such a study is appropriate to be done and it is observed that the total deformations and shearing stresses, occurred in both barrels are within acceptable values. After the removal of trapezoidal screw threads on the 120 mm mortar barrel, it was seen from the analysis results that there was no negative situation in terms of mechanical strength in the barrel, and therefore it was found to be safe and reliable for use.

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Contribution in the current study: He conducted study by, thermo-mechanical analysis for the stresses affecting during firing of the currently used 120 mm mortar with a screw thread were investigated by ANSYS Workbench finite elements method.

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Contribution in the current study: He contributed in study of the status of the mortar after removing the screw threads, which was examined in the ANSYS Workbench program under the effect of the same stresses and the results were compared between the two mortars and it was examined whether it is safe to remove the screw threads.