Light Weight Aluminum Cartridge Case Design for IED's Application - ANSYS

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Abstract: This paper describes the design analysis of the aluminum cartridge case, its testing, Analytical Simulation (ANSYS) and evaluation against Improvised Explosive Devices (IEDs) applications. Aluminum material is light in weight, non-corrosive and compatible with the propellant. Because of excellent properties, it is widely used in defence application sector. In the armament system, an effort is being made to reduce the cost, the weight of material from logistic point of view and its manufacturing process so as to meet the design requirements. Brass cartridge cases are being widely used in various types of ammunition for last 100 years *e.g.* armaments of small arm cartridges, artillery shell and power cartridges for fighter aircraft. Cartridges are made of either aluminum, steel or brass is filled with the propellants and pyrotechnic composition. With suitable means of ignition, the propellant generates the hot combustion gases at high pressure and temperature. These combustion gases are utilized to perform certain work on the system. The aluminum cartridge case for water disruptor applications plays a significant role in the destruction of the suspicious objects. This paper discusses the design aspects of the aluminum cartridge case for disruptor application of suspected IEDs. Performance evaluation parameters *i.e.* maximum pressure (P_{max}) and time to reach maximum pressure (TP_{max}) of aluminum cartridge have been carried out in a Closed Vessel (CV) using a Data Acquisition System (DAS). The material properties of aluminum such as tensile strength, percentage elongation and yield strength are determined using a Universal Testing Machine (UTM). Using the data obtained by the above methods, an attempt has been made to determine stress, strain and deformation of the cartridge case theoretically and numerically using ANSYS software. The results obtained by both methods are compared. The results are in good agreement with each other. It is observed that the percentage error for von -Mises stresses is 10.2 % using numerical and theoretical approaches. The percentage error between numerical and theoretical values of the hoop and longitudinal stresses are 6.71 % and 6.78 %. The percentage error between numerical and theoretical values of the hoop and longitudinal strains are 1.36 % and 3.64 %. The errors between theoretical and numerical values for radial displacements are 2.83 %. The novelty in this research work is that the design analysis of aluminium cartridge case is carried out using ANSYS software simulating the real-world problem. The analytical results are compared with numerical results. The actual pressure experienced by the cartridge case generated by the propellant burning is taken into consideration. This pressure is measured by a pressure transducer fitted over a specially designed test rig using a DAS. The sample of aluminum case is tested for hardness and microstructure. The results show there is no significant difference before and after the hardness and microstructure of the material. The results of ANSYS for stress and strain are in good agreement with theoretically calculated results and numerical analysis as percentage error is less than 11. This draws the inference for validating numerical and theoretical results. It is seen that 57.352 % saving in weight using aluminum cartridge is achieved. Using ANSYS, hoop stress 382.7 MPa, Hoop strain 4.32×10^{-3}, longitudinal strain 0.8602×10^{-3} and longitudinal stress 191.5 MPa are estimated. The main objective of this paper is to carry out design and analysis of aluminum cartridge case analytically as well as numerically.

Keywords: ANSYS, Cartridge, Closed Vessel, Disruptor, IEDs and Power cartridge.

1. INTRODUCTION

1.1. Cartridge Case

Design and analysis of any component play a very important role before its actual use in the system. The main objective of the paper is to carry out the design analysis of aluminum cartridge case. This design validation aids to demonstrate how the system will perform its intended function. The analysis gives a fair idea whether the component will survive during actual field trials. Power cartridge in a disruptor application utilizes aluminum as a material for construction. On initiation of the cartridge, it provides the gas pressure due to the propellant burning. This phenomenon of converting solid to gas poses a rapid chemical reaction liberating energy instantaneously. Power cartridges are gas generators consisting of a squib as a means of initiation, booster and the propellant. They are used to perform the destruction task of dangerous objects [1]. The water jet is produced and effective against suspected objects including IEDs. The various materials are being used in the manufacturing of cartridge cases such as brass, steel and aluminum depending upon cost, compatibility of explosives and its availability. A similar study was presented by Parate *et al.* [2] for design analysis of cartridge case using brass material. Using a brass cartridge case, the maximum and minimum hoop stresses are 315. 9 MPa and -5.2 MPa, the maximum and minimum von-Mises stress are 356

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MPa and 11.8 MPa and maximum and minimum radial stress are 176 MPa and -109 MPa. The maximum and minimum hoop strains are 0.0033 and 0.00115. A study described the various stresses that brass cartridges case experience during the actual field trials. Studies regarding the metallographic inspection of rifle brass cartridge using scanning electron microscopy (SEM), optic microscopy and X ray energy dispersive spectrometry (EDS) was reported by Pichipila *et al.* [3]. During the firing process, the deformation of the steel cartridge case was very intricate. It was complicated to reproduce the interaction between the chamber and the cartridge case. To study this problem, the semi-closed bomb test was an important means. Never-the-less due to technical limitations, the method does not spontaneously obtain the deformations, force pertaining to the cartridge and different parts of the chamber. The semi-closed bomb test method was used to launch a projectile of steel cartridge with different chamber pressures reported by Zhao *et al.* [4]. During the rolling of Cu-Zn30 of brass material, the strain change path on grain refinement and cryogenic temperature effect was determined by Konkova *et al.* [5]. For many years the research on the use of light weight case material has been going on.

The novelty in this research article is that the internal pressure realised by the propellant burning was measured using a DAS in a specially designed test rig. The pressure measured in this test rig is 63 MPa which is considered a valuable input for aluminum cartridge case design and its numerical analysis [6]. In the earlier work the pressure was recorded in a CV with an order of 16.08 MPa. Experimental, numerical analysis and power cartridge characterisation using brass material for disruptor application was discussed by Parate *et al.* [7]. A numerical and experimental study was conducted by Eugen *et al.* [8] had evaluated the drawing efficiency of 60820 temper aluminum alloy for cartridge tubes. The validation of the theoretical assessment was carried out by superimposing the graph of stress triaxiality ratio *vs.* plastic strain and graph of 60820 temper Al alloy fracture envelope for a zero load parameter. Comparative studies of combustible materials such as foam based on polymer-bonded RDX and traditional felt used in cartridge cases was reported by Wei *et al.* [9]. The measurement of external temperature on aluminium cartridge case of 9 mm calibre using a thermal imaging camera was reported by Gashi *et al.* [10]. After conducting a series of experiments, they inferred that aluminium reached a higher temperature than brass. Finite element modeling of small calibre of primer pre-seating was investigated by Kevin *et al.* [11] during production. Force equilibrium, deeper penetration and stamping was simulated through experiments. Aluminium cartridge case for IEDs applications are explored and developed through a specially designed test rig in a laboratory, without much inference in the open literature.

1.2. Research Objective

The objective of this research study was to investigate the aluminum cartridge design aspects and demonstrate the concept of light weight cartridge case for a water jet application. Weight saving was achieved without compromising the functionality of ammunition. Different mechanical properties such as stress, strain and deformation of the aluminium cartridge case are theoretically determined and compared numerically using ANSYS software. The ANSYS software is used for aluminum cartridge analysis case. The objective of this work is to carry out comparative analysis using numerical and simulation studies of aluminum cartridge case and validate its results with theoretical calculations.

2. CARTRIDGE CASE DESIGN ASSUMPTIONS

The important consideration in designing of aluminium cartridge case is the space available for loading the propellant mass. The cartridge is designed for a single shot purpose. The best source of energy for achieving the disruption of IEDs is the propellant that acts as a fuel.

2.1. Material Selection for Cartridge Case and its Manufacturing

The case is made up of aluminum material. The various points to be considered for designing the cartridge case are the maximum pressure developed inside the cartridge. The length of the cartridge is depends on breech dimensions, the propellant or booster mass and space to accommodate means of ignition. The selection of aluminum cartridge material is based on the following factors -

a) Available and cost-competitive as compared to other materials,

b) Aluminium material is light in weight due to low density compared to brass and steel,

c) Meet the obturation requirements,

d) Good for thermal conductivity and has a great potential for success,

e) Compatible with the propellant and pyrotechnic compositions,

f) The material should withstand the thermal load considering the temperature of the propellant,

g) Non-corrosive in nature and minimum health hazard,

h) The requirement of the case is to accommodate the squib, the propellant mass and to sustain high pressure and temperature gas.

2.2. Design Considerations for the Cartridge Case

The thickness of the cartridge is determined based on the calculations made using thin cylinder theory, where d (inner diameter) > 10 t (thickness). The following assumptions are made to the problem statement

a) The cylinder is made of homogenous material

b) Circumferential or hoop stress is uniformly distributed

c) Young modulus in tension or compression is the same

d) Plane section perpendicular to the longitudinal axis of cylinder before loading remains plane after loading

e) The magnitude of the hoop and longitudinal stresses are constant across the wall thickness and radial stress is being very small. It is neglected in comparison with the other two.

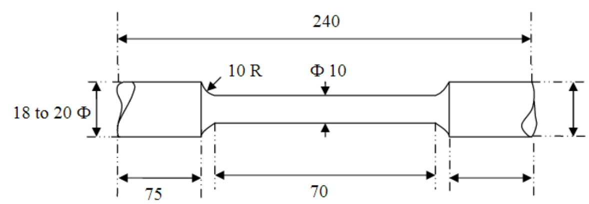
3. MATERIALS AND TECHNIQUES

3.1. Description of Aluminum Cartridge Case

Aluminum cartridge case is composed of various elements such as copper, silicon with other impurities such as iron, magnesium and manganese. The mechanical properties of aluminum material are modulus of elasticity 68 GPa, proof stress 300 MPa, Tensile ultimate strength 495 MPa, hardness 123-139 HV, percentage elongation 7 and Poisson's ratio is 0.33. The tensile test was performed on aluminum specimen having dumbbell shape. The stress-strain profile is obtained by subjecting test specimen on Universal Testing Machine (UTM). The standard test piece is fabricated and subjected to gradual loading till it gets fractured. The test specimens in the form of dumbbell with engineering drawing, images before and after testing of aluminum material are illustrated in Figure **1**. The stress - strain profile obtained experimentally using UTM is shown in Figure **2**. The aluminum cartridge material used for this application has yield strength of 400 MPa [12]. The mechanical properties and % elements presents for aluminium material are given in Table **1**.

Table 1:

Mechanical Properties		% Elements Present	
Modulus of elasticity	68 GPa	Copper	4.31 %
Proof stress (0.2 %)	300 MPa	Silicon	0.84 %
Ultimate strength	495 MPa	Iron	0.18 %
Yield strength	400 MPa	Magnesium	0.36 %
Elongation	7 %	Manganese	0.67 %
Poisson's ratio	0.33	Aluminum	Remainder



1 (a). Engineering drawing of a test specimen.

1 (b). Aluminum photo specimen before test.

1 (c). Aluminum photo specimen after test.

Figure 1: Engineering drawing of test specimen.

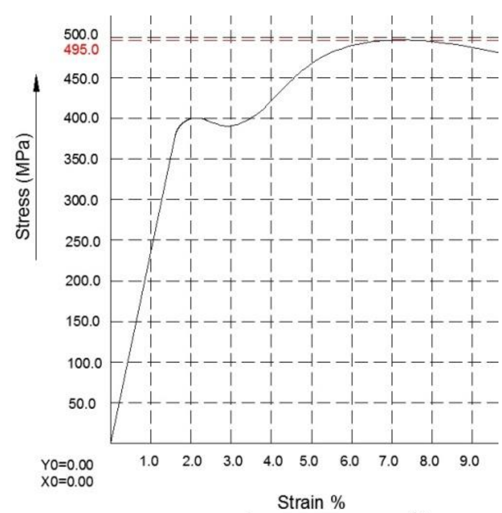


Figure 2: Stress - Strain curve for aluminum material.

3.2. Dimensions of the Cartridge

The dimensions of the cartridge height and flange thickness are selected as per the dimensions of the breech module where it is fitted. The dimensions of the cartridges are given in Table **2**.

Table 2: Dimensions of the Cartridge

Dimensions	Unit (mm)
Total Length	54.5
Outer diameter	20
Internal diameter	17
Thickness	1.25

The image of aluminum cartridge case is depicted in Figure **3**.

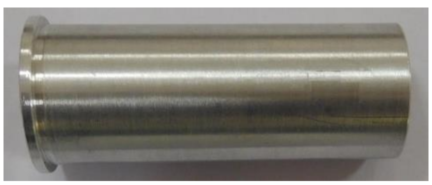


Figure 3: Image of aluminum cartridge case.

4. EXPERIMENTAL WORK

4.1. Test Arrangement to Measure the Pressure by a Data Acquisition System

The main principle of a piezoelectric quartz transducer is that pressure, when applied on it, produces electric charges on the crystal surface and vice versa. The charge thus produced can be called piezoelectriccity. It is defined as the electrical polarization produced by mechanical strain on certain crystals. The rate of charge produced is proportional to the rate of change of applied pressure as input. As the charge produced is very small, a charge amplifier is needed so as to produce an electrical output. The pressure sensor has a sensing element of the constant area and responds to applied pressure to this area by a gas pressure. The applied pressure will deflect a diaphragm inside the pressure sensor. The deflection of the internal diaphragm is measured and converted into an electrical output. This allows the pressure to be monitored by microprocessors, programmable controllers and computers along with similar electronic instruments. A pressure sensor is a device which senses applied pressure and converts it into an analog electric signal whose magnitude depends upon the applied pressure.

An experimental test arrangement consists of Velocity Test Rig (VTR), charge amplifier and DAS. Pressure sensors and charge amplifiers are the essential parts of the DAS. A VTR is designed, fabricated and tested in the laboratory. The DAS for the pressure measurement system comprises of the cartridge, gauge adaptor, a VTR and Yokogawa scope corder DL 850E. It has a 12 bit module with a sampling rate of 10 MHz and a charge amplifier. The measurement chain comprises of a pressure sensor, charge amplifier and output from the scope corder. Figure **4** illustrates the measurement chain. The cartridge is initiated on the application of 24 V DC. Gases are generated on burning of the propellant. This is a working fluid acts against the projectile. A hole of 5 mm diameter is drilled through the body of a VTR as a pressure take-off point. The volume of ~15 cm^3 is available (length 15 mm and internal diameter 36 mm) for the expansion of the gases ahead of the projectile. A pressure sensor is screwed into the body in a radial direction perpendicular to a VTR body axis. This signal is being small and is further amplified by a charge amplifier. A pressure sensor, charge amplifier and scope corder are connected by a low noise cable. The commercial pressure sensor (Kistler make) is selected to have a fast response, small size, durability,

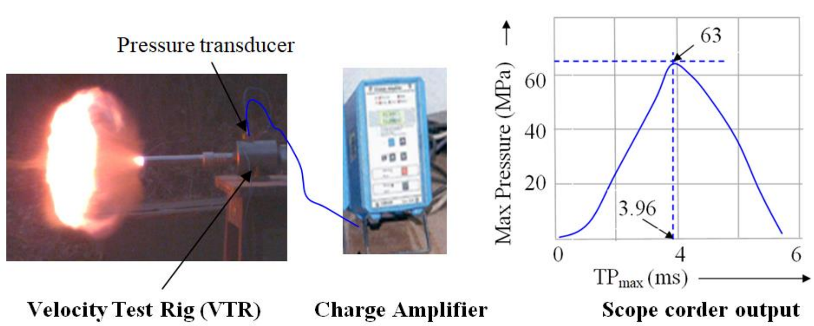


Figure 4: Data acquisition system showing VTR, charge amplifier and scope corder output.

hermetically sealed construction, measurement range 15000 PSI, sensitivity 0.39 pC/psi and a rise time of ≤ 1 μ s.

5. NUMERICAL ANALYSIS

A static structural finite element analysis of the cartridge case is carried out using ANSYS software. Actual drawing dimensions of the case were used for modeling. The model is rotationally symmetric about Z-axis. The model is constrained at a step so to simulate the fitting of the cartridge in real-time scenario. A 3D model of the cartridge case is shown in Figure **5**.

Figure 5: A 3D model of the cartridge case.

5.1. Meshing

The meshing is carried on the geometry before applying the load conditions to generate FE model. For meshing purpose, a dedicated meshing platform named Hypermesh is used. The meshed geometry is shown in Figure **6**.

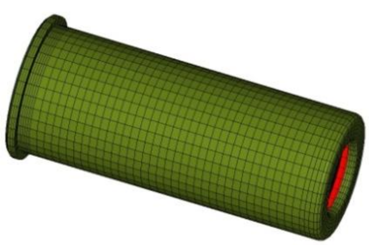


Figure 6: Mesh geometry.

6. ANALYTICAL ANALYSIS

6.1. Theoretical Estimation of Stresses

The various stresses such as hoop stress, longitudinal stress and equivalence stress with strains are determined by taking mechanical properties mentioned in Table **1** obtained during tensile testing and actual values of dimensions as given in Table **2**. The calculations as an example are illustrated as below:

a) Hoop Stress (σ_h)

The design of the cartridge case based on Hoop stress which is predominant [13,14].

$$\sigma_{\mathrm{h}} = \frac{P_{\max}\ r_i}{t} \tag{1}$$

where,

t_c Cartridge wall thickness= 1.5 mm

P_{max} Max pressure generated in the case = 63 MPa

r_i Internal radius of the case = 8.5 mm

$$\sigma_{\mathrm{h}} = \frac{8.5\times 63}{1.5} = 357 \text{ MPa}$$

Strain in the case $= \dfrac{\sigma_{\mathrm{h}}}{\mathrm{E}_{\mathrm{case}}} = \dfrac{357}{68\times10^{3}} = 5.25\times10^{-3}$

b) Longitudinal Stress (σl)

Longitudinal Stress will be half the value of Hoop Stress

σ_l = 178.5 MPa

c) Equivalent von-Mises stress acting on cartridge

$$\sigma_{\mathrm{eq}} = \sqrt{\sigma_h^{\ 2} + \sigma_l^{\ 2} - \sigma_h \times \sigma_l} = 309.17 \text{ MPa} \tag{2}$$

d) The Outer Diameter (OD) of the case (tc) can be determined as follows –

$$d_o = d_i + 2\ t_c = 17 + 2\times1.5 = 20 \text{ mm} \tag{3}$$

e) Radial expansion the case

$$= \frac{P\, r_{\mathrm{o}}^{\ 2}}{\mathrm{t}\ \mathrm{E}_{\mathrm{case}}} = \frac{10^2\times 63}{1.25\times 68\times10^{3}} = 0.0741\,mm$$

f) Maximum shear stress in the case

$$= \frac{(\sigma_h - \sigma_i)}{2} = 89.25\ MPa$$

g) Maximum expansion of the case = Radius of the case × strain = 44.625 × 10^{-3} mm

6.2. Theoretical Estimation of Strains

a) Hoop Strain (ε_{h})

Hoop Strain is calculated by the following equation

$$\varepsilon_{\mathrm{h}} = \frac{1}{E}(\sigma_{\mathrm{h}} - \mu\,\sigma_{\mathrm{l}}) \tag{4}$$

Where

E Young Modulus of aluminum material = 68 GPa

μ Poisson's ratio = 0.33

$$\varepsilon_h = \frac{1}{68\times10^3}(357 - 0.33\times178.5) = 4.383\times10^{-3}$$

b) Longitudinal Strain (ε_h)

Longitudinal Strain is calculated by the following equation

$$\varepsilon_l = \frac{1}{E}(\sigma_l - \mu\,\sigma_h) \qquad (5)$$

Where

$$\varepsilon_l = \frac{1}{68\times10^3}(178.5 - 0.33\times357) = 0.892\times10^{-3}$$

It is noted that Hoop strain is more than longitudinal strain.

7. RESULTS AND DISCUSSION

7.1. Results

The numerical and analytical values are determined as explained in above paragraphs. The various plot contours for hoop stress, von-Mises stress, longitudinal stress, hoop strain, longitudinal strain and maximum displacement obtained by ANSYS simulation are given at Figures (**7-12**) respectively. Figure **7** shows the hoop stress is 382.7 MPa. Figure **8** shows the von-Mises stress is 344.3 MPa. Figure **9** shows the longitudinal stress is 191.5 MPa. Figure **10** shows the Hoop strain $4.32\text{x}10^{-3}$. Figure **11** shows the longitudinal strain $0.8602\text{x}10^{-3}$. The maximum displacement is shown in Figure **12**. The comparative theoretical and numerical analyses are given in Table **3**.

From Table **3**, it is observed that the percentage error for von-Mises stresses is 10.2 % using numerical and theoretical. The percentage errors between numerical and theoretical values of hoop stresses and strain are 6.71% and 1.36 % respectively. The percentage errors between numerical and theoretical values of longitudinal stresses and strain are 6.78 % and 3.64 %.

7.2. Discussions of Results

There is a marked difference between the values of stresses particularly Hoop stress. Numerical hoop stress is greater as compared to theoretical calculation using thin cylinder theory.

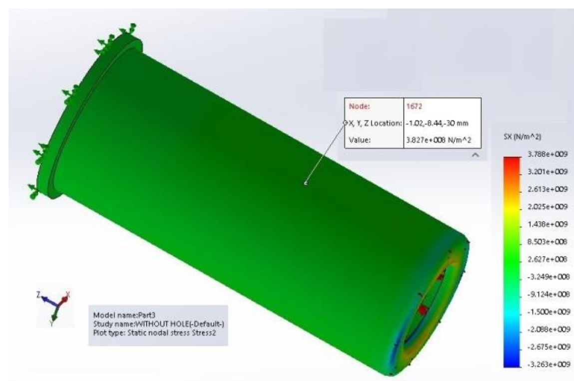


Figure 7: Hoop Stress plot.

Ballistic performance parameters evaluation is carried in a (VTR) designed and fabricated in house. After the completion of numerical simulation, a series of firing trials are carried out in a VTR. Smooth extraction and no bulging were observed in all cases. The images of cartridges after a series of firings are depicted in Figure **13**.

Table 3: Numerical, Theoretical Values of Stresses and Strains

Mechanical Parameters	Theoretical	Numerical	% Error
Hoop stress	357 MPa	382.7 MPa	6.71
Longitudinal stress	178.5 MPa	191.5 MPa	6.78
Shear stress	89.25 MPa	--	--
Hoop strain	4.38×10^{-3}	$4.32\text{x}10^{-3}$	1.36
Longitudinal strain	0.892×10^{-3}	$0.860\text{x}10^{-3}$	3.64
von-Mises stresses	309.17 MPa	344.3 MPa	10.2
Radial expansion of case	0.072 mm	0.0741 mm	2.83

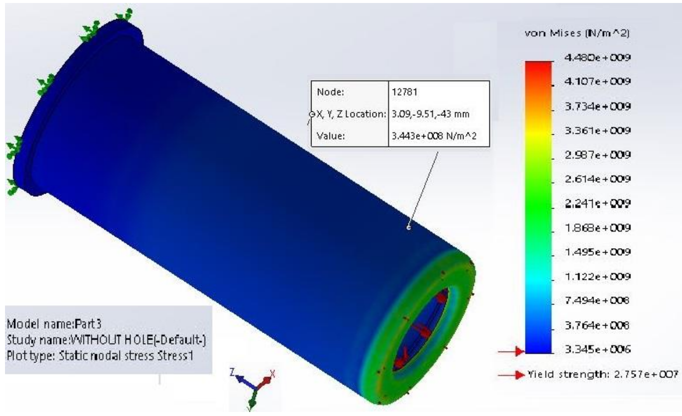


Figure 8: von - Mises Stress plot.

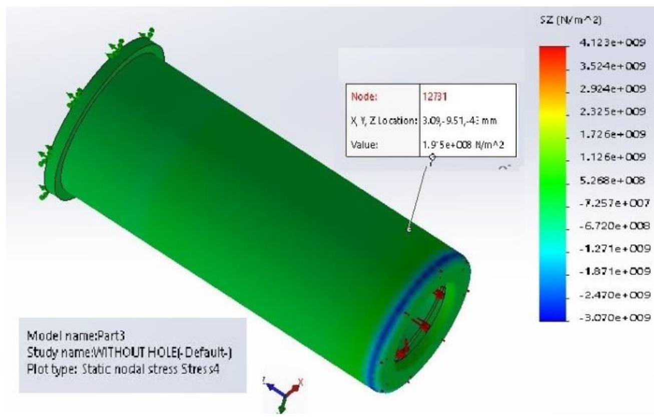


Figure 9: Longitudinal stress plot.

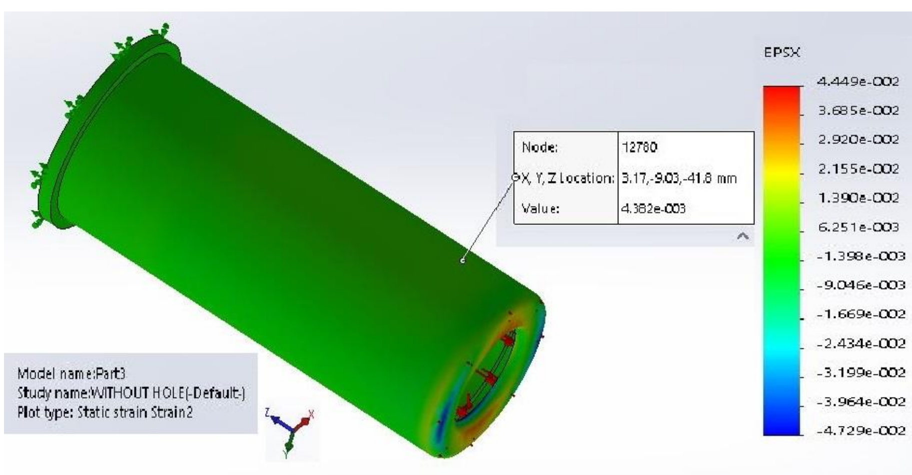


Figure 10: Hoop Strain plot.

7.3.Metallurgical Testing

After cartridge firings, the cut section of Al case is subjected to a hardness test and microstructure analysis. The hardness of the cartridge case is measured at 5 kg load from the base diameter to tip (*i.e.* left to right) as depicted at Figure **14(a)**. After the analysis, it is inferred that there are no changes in the hardness of the material. The cut section for measuring the hardness of the cartridge case and sample preparation for microstructure after the firing is shown in Figures **14(a** and **b)**. Cartridge case are etched with HF solution for the microstructure and then polished.

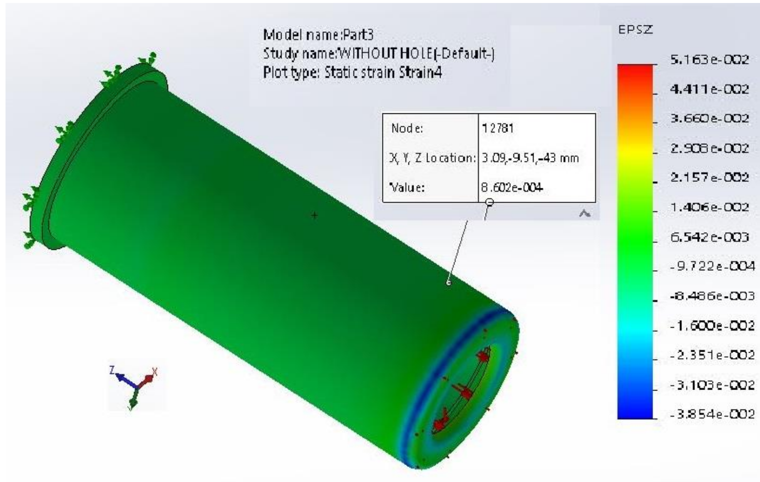


Figure 11: Longitudinal Strain plot.

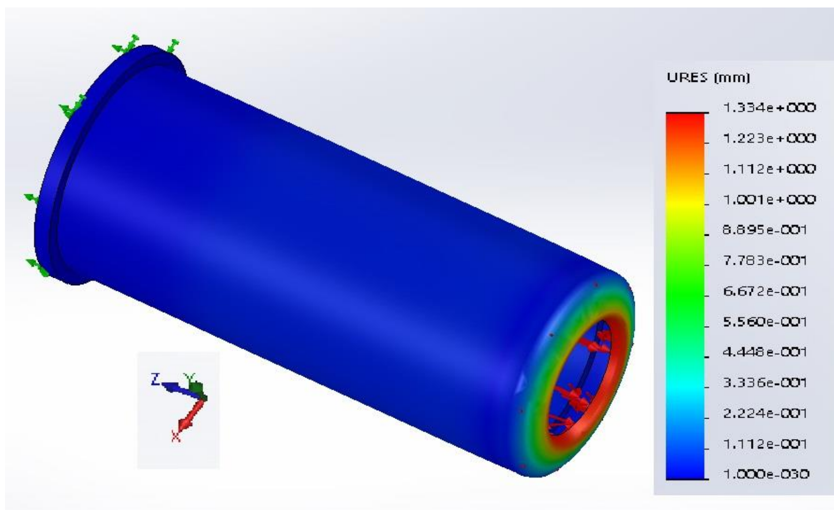


Figure 12: Maximum displacement.

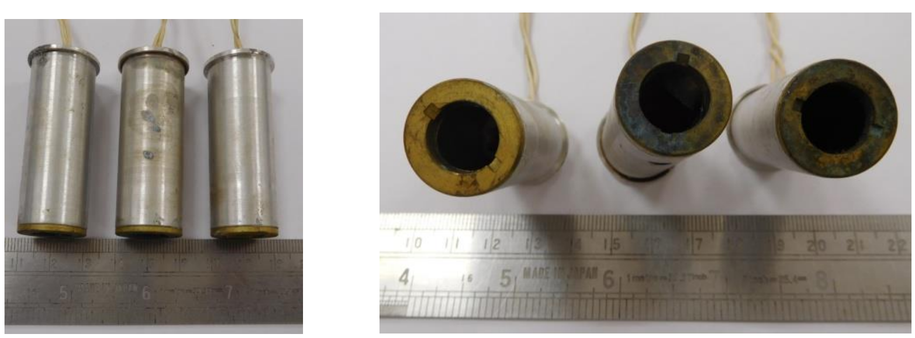


Figure 13: Images of cartridges after firings (right: side view and left: top view).

The images of the microstructure after firings are illustrated in Figures **15**. Figure **15(a)** shows enlarged view @200X in a longitudinal section. Figure **15(b)** shows an enlarged view @500X in a longitudinal section. Structure consists of the light gray particles of insoluble (Cu,Fe,Mn) Al6, Black particles of undissolved CuMgAl2 and fine particles of CuMgAl2. The micro-structures of the cartridge case before and after firings are compared and it shows the structure remains unchanged.

The hardness is measured at different locations from base to tip before and after the firing. There are no significant changes in the hardness values for the

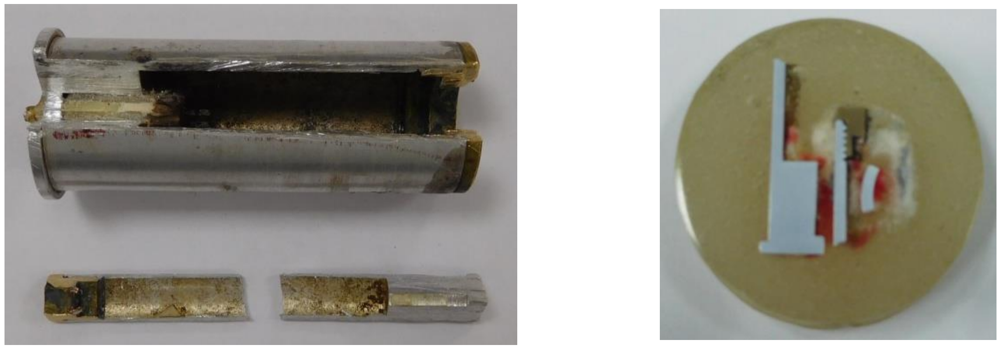


Figure 14: (**a**) The cut section for measuring hardness (**b**) Sample preparation for microstructure.

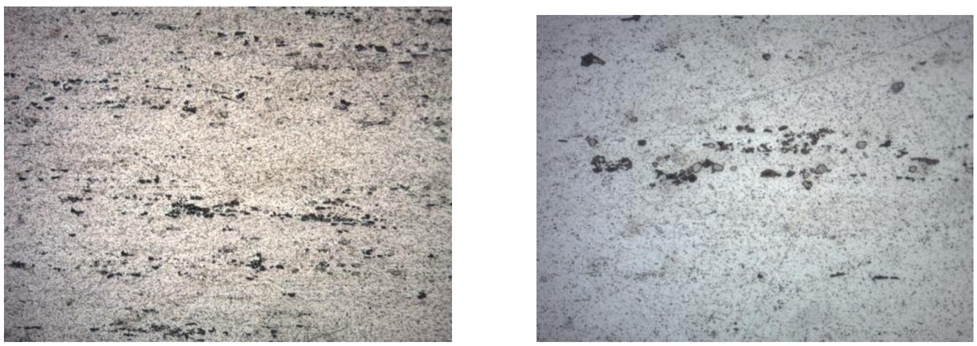


Figure 15: (**a**) shows @200X in the longitudinal (**b**) shows @500X in the longitudinal section.

cartridge case. The hardness values are shown in Table **4**.

Table 4: Hardness Values

Nomenclature	**Hardness in HV Load @ 5kg**		
Location	Base	Middle	Tip
Cartridge case	123 - 124	137 - 139	136 - 137

7.4. Comparative Cartridge Weight Analysis

The weight of complete ammunition is significantly reduced using Al case designed and tested without compromising a safety and effectiveness of the system. The cartridge case design concept is developed which aids in reducing the cartridge weight. Further reduction in cartridge weight reduces the burden during logistic. This helps the troops to carry out more additional ammunition that will improve the battle effectiveness.

The comparative analysis of aluminum and brass cartridge case on a percentage weight basis at various components levels are given at Table **5**.

From the above table **5**, it is seen that 57.352 % of saving in weight using aluminum cartridge is achieved. This is a significant saving in terms of cost and material. Further, this reduces the logistic burden on troops carrying out such kind of ammunitions.

Table 5: Comparative Analysis of Aluminum and Brass Cartridge Case

Aluminum		**Brass**	**Percentage Weight Reduction**
Components	**Weight (g)**	**Weight (g)**	$= \frac{(66.853 - 28.511)}{66.853}$ = 57.352
Case	19.152	57.494	
End cap & foil assembly	6.159	6.159	
Weight with explosive	3.2	3.2	
Total weight	28.511	66.853	

8. CONCLUSION AND RECOMMENDATIONS

The objective of this paper is achieved using the proper selection of the material without affecting safety aspects and performance parameters of the cartridge case. The FE analysis using ANSYS is carried out on aluminum cartridge case to determine the various stresses, strains and deformations. Theoretical calculations are also made using thin cylinder theory to have a general calculation of stresses in the cartridge case. Based on the above analysis, a research paper presents results of combination of theoretical and computer simulation for design and analysis of the power cartridge using aluminum material. The design concept has offered a 57.352 % weight reduction as compared to the conventional brass cartridge case.

By comparing the numerical results with the experimental data, the following inferences are drawn:

FEA predicts the results more accurately due to the following reasons -

a) Cartridge aluminum case is effectively utilized for disruptor application with caliber of 20 mm. Such type of study shall be further extended for a bigger caliber application.

b) Aluminum case design, testing and its analysis is successfully brought out in this paper. Aluminum material is less expensive than conventional brass cartridge case. Hence, it is recommended for IEDs application and future light weight ammunition system.

The results of theoretical and numerical analysis for the hoop and longitudinal stress and hoop and longitudinal strains are in good agreement as percentage error is less than 7 %. This draws the inference for validating both the numerical and theoretical results.

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CONFLICT OF INTERESTS

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SYMBOLS, NOMENCLATURE AND UNITS

Symbols	Nomenclature	Unit
A	Area	mm^2
E_{case}	Modulus of elasticity of case	GPa
P_{max}	Max pressure generated in the case	MPa
r	Radius of the case	mm
t	Cartridge wall thickness	mm
Greek Symbols		
π	Constant (3.14)	--
ε	Strain developed in the case	--
υ	Poisson's ratio	--
σ	Stress developed in the case	MPa
Subscript		
h	Hoop	--
l	longitudinal	--
i	Internal	--
o	Outer	--

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