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Research Article

Nonlinear Material Behavior Analysis under High Compression Pressure in Dynamic Conditions

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Gun chamber pressure is an important parameter in proofing of ammunition to ensure safety and reliability. It can be measured using copper crushers or piezoelectric sensor. Pressure calculations in copper crusher method are based on linear plastic deformation of copper after firing. However, crusher pressure deformation at high pressures deviates from the corresponding values measured by piezoelectric pressure transducers due to strain rate dependence of copper. The nonlinear deformation rate of copper at high pressure measurements causes actual readings from copper crusher gauge to deviate from true pressure values. Comparative analysis of gun chamber pressure was conducted for 7.62 × 51 mm ammunition using Electronic Pressure, Velocity, and Action Time (EPVAT) system with piezoelectric pressure transducers and conventional crusher gauge. Ammunitions of two different brands were used to measure chamber pressure, namely, NATO standard ammunition and non-NATO standard ammunition. The deformation of copper crushers has also been simulated to compare its deformation with real time firing. The results indicate erratic behavior for chamber pressure by copper crusher as per standard deviation and relative spread and thus prove piezo sensor as more reliable and consistent mode of peak pressure measurement. The results from simulation, cost benefit analysis, and accuracy clearly provide piezo sensors with an edge over conventional, inaccurate, and costly method of copper crusher for ballistic measurements due to its nonlinear behavior.

1. Introduction

Proof is a destructive test in which small numbers of proof samples are selected as representative of a large group known as lot or batch of the ammunition by the same manufacturer and process. Proofing of ammunition is important to ensure the safety, reliability, and operational effectiveness of conventional ammunition. The importance of proofing is often poorly understood, leading to failure in ammunition safety and stability. Proof of ammunition is a systematic method of evaluating the properties, characteristics, and performance capabilities of ammunition throughout its life cycle. It is used to assess the reliability, safety, and operational effectiveness of stocks. Proof is the functional testing or firing of ammunition and explosives to ensure safety and stability in storage and intended use. In-service proof and the surveillance of ammunition are undertaken to ensure that the ammunition continues to meet the required quality standards throughout its life [1].

The acceptance or rejection criterion during test firing of guns and ammunitions depends upon many factors. Chamber pressure is defined as the force per unit area that explosive gas exerts on the walls of a gun chamber. Chamber pressure being the most important, researchers have been making unremitting efforts to improve the testing precision [2] as this must be tested and verified during research and development of product acceptance.

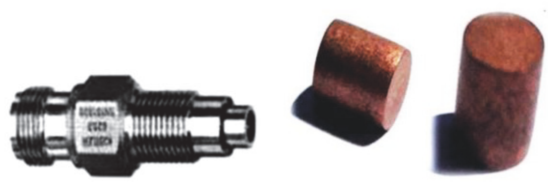

Figure 1: Piezoelectric sensor and copper crushers.

Crusher gauges were used to measure gas chamber pressure as commonly available standardized method till 1960s [3]. Usually a piston fitted to a piston hole into the chamber of the barrel compresses a copper or lead cylinder. The crusher gets permanently deformed due to the effect of the gas pressure generated by the burning of the explosive mixture on the base of the piston. After measuring the deformed crusher length, the peak pressure is estimated after comparing it to a calibrated conversion table provided by the manufacturer with each lot of crushers. Though convenient, it is incapable of recording the dynamic change of chamber pressure with time. Figure 1 shows piezo sensor and conventional cylindrical copper crusher.

With the development of charge amplifiers by W. P. Kistler in 1950s piezoelectric techniques were used in the area of interior ballistics [3] which led to the use of piezoelectric transducers over crusher gauges thus making it convenient to plot accurately pressure time curve in 1960s [4].

NATO [5–7], CIP [8], and SAAMI [9] are providing insight into research and development in the field of crusher and piezoelectric pressure measurement. Pressure measurement method used by these organizations is differentiated by the measurement point and the measuring techniques. Thus, NATO standard Kistler type 6215 and the conformal PCB type 117B104 piezoelectric pressure transducers were developed by various manufacturers [3].

Copper crushers and piezoelectric sensor methods both have their pros and cons for chamber pressure measurement. Copper crusher technique is simple enough to obtain a rapid estimation of the peak pressure in ammunition testing but it has drawbacks for being of limited accuracy and only gives the peak pressure [3]. Similarly, for higher pressures the deformations noted are lower in comparison to that obtained through piezoelectric sensors due to nonlinear variations which are observed in copper material. While piezoelectric pressure sensors offer the advantages of high sensitivity, good linearity, low hysteresis, and versatility, their main use is in higher cost and precision areas [10].

The crusher pressure readings may deviate quite considerably from the corresponding values measured by piezoelectric pressure transducers. The pressure readings obtained by crushers from different manufacturers are not consistent. It has become clear that the crusher and piezoelectric pressure transducer readings differ, depending on the pressure range and the used gun type, by as much as up to +20%, and that the deviation normally increases with pressure [11]. It is anticipated that the gun pressures in the future will be increasing, which means that the difference between pressure readings obtained by different measurement techniques is also going to increase.

Piezoelectric pressure transducers give the voltage at each stage of burning (starting from ignition by primer till complete burning) which is translated in the form of a graph; hence it helps in getting the voltage peak which in turn is converted into pressure through amplifier system. Since it gives exact voltage peak achieved during the combustion in chamber, hence it is useful in exactly knowing if the pressure is not crossing the allowed safety limits of gun chamber.

In our experimental study the chamber pressure was measured by the two different techniques (crusher gauges and piezoelectric sensors) for the "ammunition type 7.62 × 51 mm." This research will try to give an insight into the following knowledge gap areas for "ammunition type 7.62 × 51 mm" not explored previously:

(i) Nonlinear behavior of copper crusher gauge material parameters at high pressure

(ii) Comparison of chamber pressure values made for copper crusher gauge and piezoelectric sensors under the same controlled test conditions

(iii) Similar caliber ammunition type "7.62 × 51 mm" used to explore the possibilities of error in crusher gauges from different ordnance manufacturers, that is, NATO standard ammunition versus non-NATO ammunition

(iv) Another prime objective of cost benefit analysis for copper crusher gauges with piezoelectric sensors also not done by other researchers previously.

1.1. Copper Crusher Pressure and True Pressure. True pressure is that value of maximum gas pressure which actually exists and would be obtained from an ideal measuring system. Accuracy of a gauge is its ability to record or measure the "true" pressure without systematic error. True pressure is that value of maximum gas pressure which actually exists and would be obtained from an ideal measuring system [12]. Pressure measured by copper crusher gauge is always less than the true pressure due to the following reasons:

(i) Inertia inherent in the system

(ii) Consequent time required to compress the copper

(iii) Very transient nature of the peak pressure in a gun.

Previously, pressure measured by copper gauges was accepted as true pressure but, with the advent of inertialess gauges, it has been found that there is a reasonably constant relationship between pressure on copper and that measured by an inertialess gauge (true pressure) [13]. For present purposes modern transducer systems which record pressure as a time function are accepted as giving the best available estimate of "true pressure" [12].

2. Methodology

EPVAT testing is well-established NATO proofing system for proofing/inspecting of ammunition and ensures

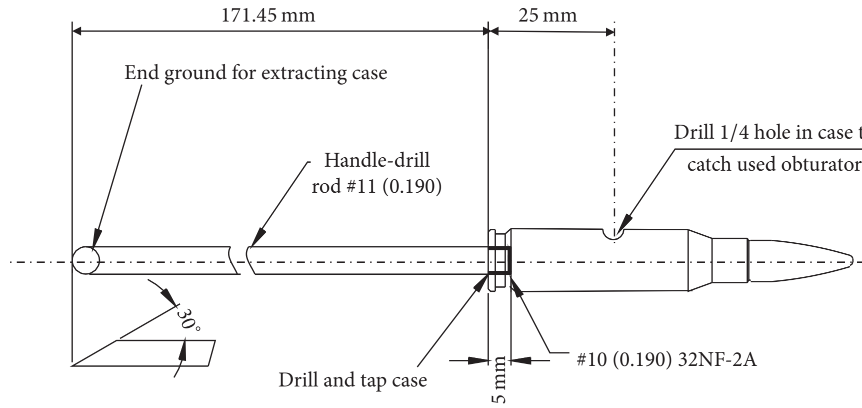

FIGURE 2: Drawing for preparing proof cartridge [05].

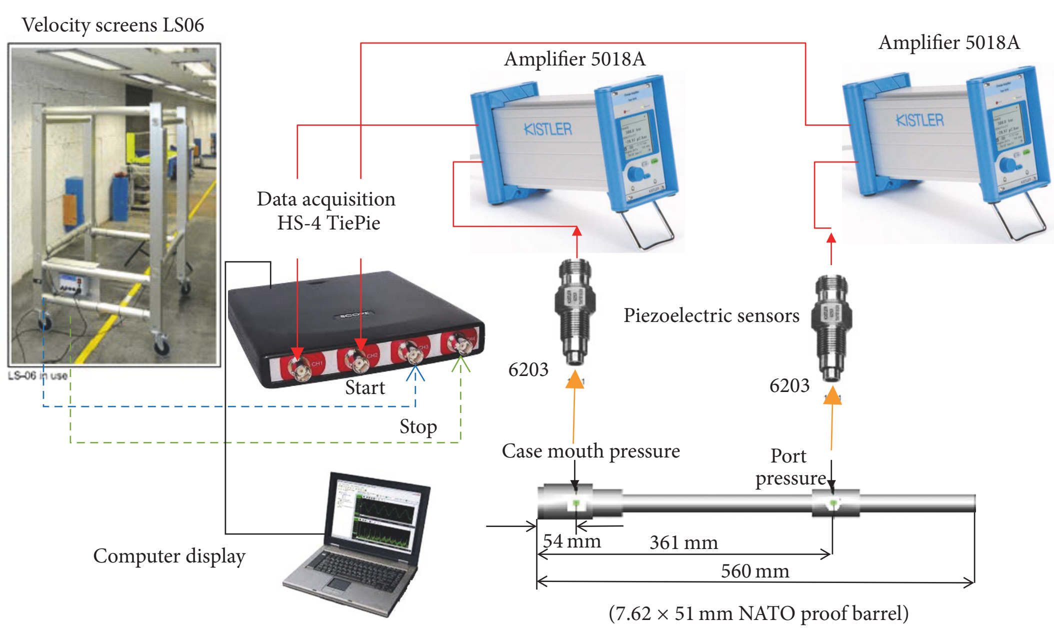

FIGURE 3: Schematic of Electronic Pressure, Velocity, and Action Time.

safety/quality. This procedure ensures the safety of the shooter and its 100% functionality at the target. It is a comprehensive procedure for testing ammunition using state-of-the-art instruments and computing devices. The procedure itself is described in NATO MOPI document AC/225 (Com. III/SC.1)D/200 [14].

The MOPI manual also provides guidelines to prepare cartridge cases for using copper crusher method. Figure 2 shows drawing layout for preparing cartridge.

In EPVAT system, case mouth pressure, port pressure, action time, and velocity of a bullet are measured simultaneously. This NATO system clearly defines piezoelectric sensor locations on the barrel, magnitude of pressure limits, bullet energy, action time, and velocity limits against a particular caliber, thus providing a unique opportunity to enhance quality of ammo. Action time is defined as the time that requires bullet to leave muzzle end from the ignition of bullet primer.

Internal ballistic parameters measured through EPVAT system are most important to study and analyze the effects on weapon operation, barrel length vis-à-vis velocity, recoil force, flash intensity, muzzle design, barrel redesign (if needed), and continuous propellant improvement. The schematic diagram of EPVAT system is shown in Figure 3.

NATO MOPI manual, as standard document for ballistic measurements, provides the following requirements for accurate pressure measurement through copper crusher/piezoelectric sensors [15]:

(i) The mean peak chamber pressure of any type of ammunition shall not exceed 50,000 pounds per square inch (corrected) when the ammunition is conditioned at 21°C using the radial copper pressure cylinder as required by STANAG 2310 [16].

(ii) The corrected mean peak pressure of any type of ammunition, measured at case mouth position using

Figure 4: EPVAT system for case mouth pressure measurement.

piezoelectric transducer, shall not exceed 380 MPa (corrected) when the ammunition is conditioned at 21°C as required by STANAG 2310 [16].

(iii) The weight of all bullets to be used for proofing should be within limits 8.4 to 10 grams.

(iv) The minimum average energy for a true pressure through Electronic Pressure, Velocity, and Action Time (EPVAT) barrel shall be 2915 Joules.

(v) The action time should also be limited to 4 milliseconds.

Figure 4 indicates the EPVAT system for case mouth pressure measurement. The pressure to be measured during proof fire acts on the piezo sensor's diaphragm, which converts it to a proportional force. This force is transmitted on to the quartz. Quartz has an intrinsic property of producing an electrostatic charge when subjected to load. A spring carries this negative charge till connector. The charge is later on converted to positive voltage by an amplifier.

The piezo sensor system is well suited to measure quasi-static phenomenon of rapid dynamic nature. However, amongst its limitations are static measurements for an unlimited period of time. In order to measure chamber pressure using transducers, cartridge case should have a specific clearance of 0.2 mm from transducer face to allow dynamic measurement. Figure 5 shows an actual installation of piezo sensor to measure chamber pressure.

Piezoelectric transducers are also used to measure cartridge mouth pressure and are mainly used in ammunition acceptance and testing. The installation scheme is far simpler as compared to chamber pressure because no work has to be done on to the ammunition. No drilling is required for such measurement with an important parameter of peak measurement as outcome.

Case mouth measuring scheme is presented in Figure 6. Case mouth measuring method puts a heavy load on transducers and hence shortens its life due to the fact that there is huge pressure jump at case mouth which could potentially damage transducer's diaphragm [17].

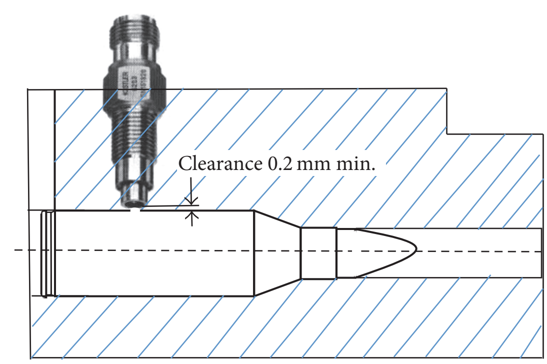

Figure 5: Piezo sensor for cartridge chamber pressure [17].

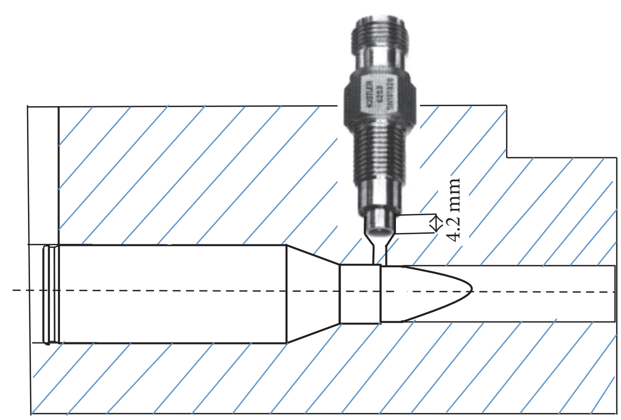

Figure 6: Piezo sensor for cartridge case mouth pressure.

3. The System Design

In normal pressure proof barrels, barrel has one drilled hole for chamber pressure measurement (either for copper crusher or for piezo transducer), whereas, in this study, a comparison of pressures measured by copper crusher as well as piezo is done at the same location using same barrel keeping all other parameters constant. Therefore, a dedicated mechanism is

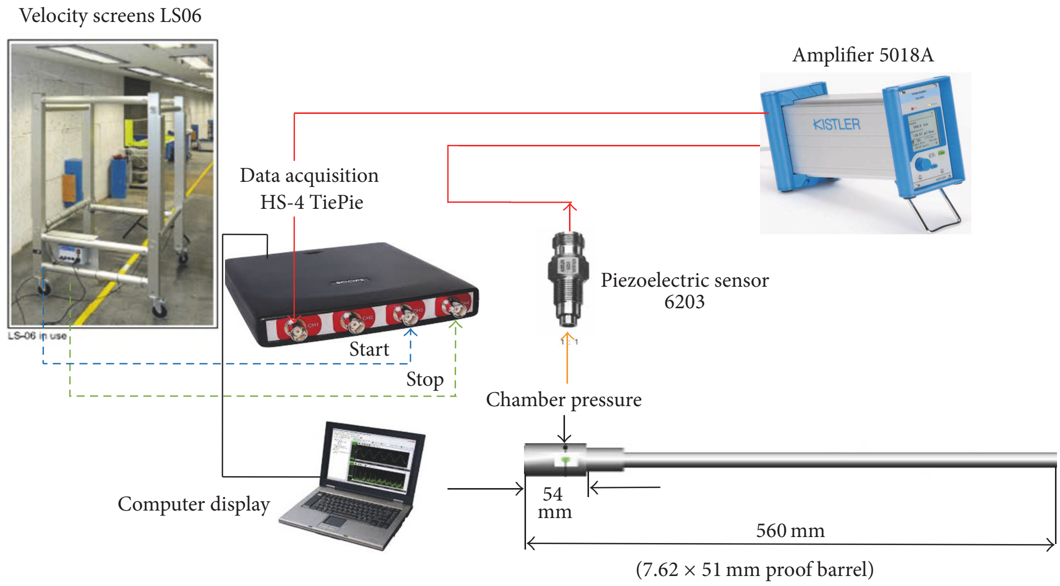

Figure 7: Schematic of chamber pressure measurement mechanism.

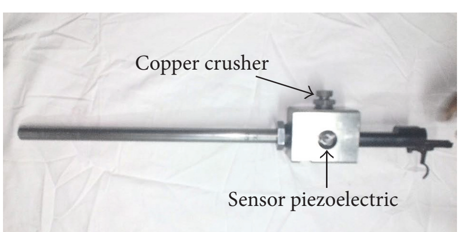

Figure 8: Barrel with 2 holes (for copper crusher and piezo pressure).

Figure 9: Barrel end with 1 hole for case mouth pressure.

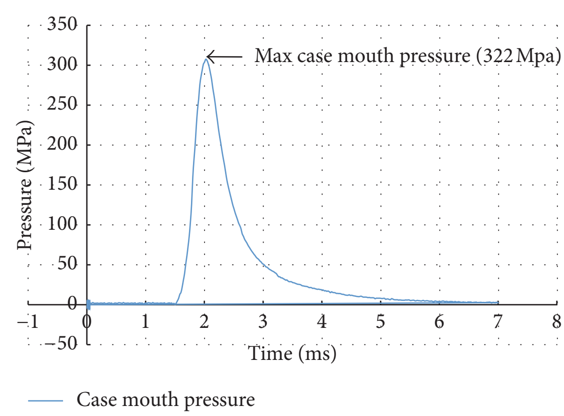

Figure 10: Pressure-time curve.

designed having provision for pressure measurement by copper crusher as well as piezo at the same distance on barrel. The salient features of the system are shown in Figure 7.

In the experimental set-up two (02) NATO proof barrels for the proofing of 7.62 × 51 mm ammo with 560 mm barrel length were manufactured: one barrel with two holes at 25 mm from chamber end (one hole for the copper crusher and the other for the piezoelectric transducer (Kistler 6203) installed at 90° to each other on proof barrel for pressure measurements as shown in Figure 8) and second barrel with single hole at the case mouth (54 mm from chamber end) as shown in Figure 9.

Figure 7 shows chamber pressure measurement mechanism where one piezoelectric transducer (Kistler 6203) was installed on proof barrel for pressure measurements and one charge amplifier (Kistler 5018A) was connected with piezoelectric transducers. The output from the sensor is fed into charge amplifier which is then passed to data acquisition system (TiePie Handy Scope HS-4, a four-channel input). Then two Light Gates (LS-06) are placed at specific distance from the muzzle end of proof barrel. When the bullet is fired two outputs signals (start and stop) are fed to the data acquisition system for velocity measurement which is used as reference in this experimental study. A data acquisition system (Handyscope HS-4) system simultaneously captures 3 signals (1 × pressure signal and 2 × velocity signals) and automatically saves raw data in specified folder as pressure-time curve as shown in Figure 10.

The customized Ballistic Data Measurement System (BDMS) software (developed in C# programing language

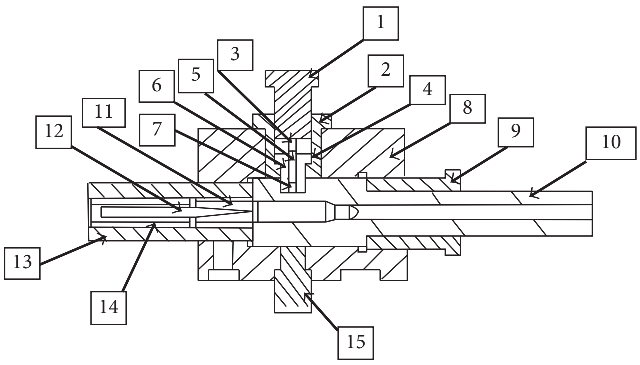

Figure 11: Mechanism for piezo and copper crusher at chamber (25 mm from chamber end) [15].

with MySQL databases) automatically detects saved raw data from a specific folder and calculates the following ballistics parameters:

(i) Case mouth pressure/chamber pressure (MPa)

(ii) Velocity (ft./s)

(iii) Energy (J)

(iv) The BDMS software automatically calculates corrected values of pressure based on the test sample and the standard rounds. The test report in PDF/MS Word and excel format is generated automatically and can be saved in a specified folder.

3.1. System Methodology. Once a round is fired for pressure measurement, the process starts with the burning of primer/ignition of propellant; hence burning of propellant generates gas pressure which is sensed by the piezoelectric transducer (Kistler 6203) as a charge signal. This signal is fed to charge amplifier (Kistler 5018A) to amplify the signal and for conversion into voltage. This voltage is fed to a smart and highly professional data accusation system and oscilloscope (HS-4 Handy scope) hence read by the computer in readable form. The setting of charge amplifier is 5000 bar/volts. So, if a signal of 0.644 v is captured, it gives pressure of 322 MPa (0.644 volts × 5000 bar/volts = 3220 bar = 322 MPa). Figure 11 shows an experimental set-up for piezoelectric and copper crusher.

4. Experimental Analysis

The results for various ammunition test fired for chamber pressure have been compared with two different experimental set-ups. The one involves a barrel having 2 holes, that is, one for copper crusher and another for piezoelectric sensor. The second manufactured barrel involves piezo only and can only measure ten rounds in each of two different categories of ammunition fired.

Experimentation was performed in order to determine material parameters and deformation behavior of copper crushers. Thereafter, extensive finite element analysis has been carried out using ANSYS after utilizing material property (elastic modulus) and density of crusher gauges. A set of tests (10 rounds in each test) were conducted by using the following parameters:

(i) Ammunitions of two different manufacturers:

(a) NATO specified standard ball ammunition labelled as NATO having propellant weight of 45.5 grams,

(b) nonstandard ammunition with cylindrical propellant labelled as NSTD also having propellant weight of 45.5 grams

(ii) Cylindrical copper crushers (4 × 6 mm)

(iii) Pressure measured against deformation of copper crusher.

Table 2 shows three different sets of experimental results as mean values for chamber pressure using 10 rounds in each test of standard NATO and non-NATO standard ammunition (ammo). The results are obtained through copper crusher using two different categories of ammunition and hence, marginal difference in values is observed.

As per NATO requirements, mean peak chamber pressure of any type of pressure shall not exceed 50,000 pounds per square inch (<345 MPa) (NATO 1997) and for case mouth mean peak pressure shall not exceed 380 MPa when ammunition is conditioned and fired at temperature 21°C (NATO 1997). On the basis of experimental analysis, deformations behavior was evaluated against the pressure given by manufacturer on a conversion table.

The pressure values noted by copper crushers during real time firing were compared with piezo transducer and it was analyzed that the pressure values observed through piezo transducer gave more precise values vis-à-vis specified (true) pressure. During the analysis, a number of firing results were obtained with the help of two different standard ammunitions fired ten rounds in each ammo test series.

The similar setting within the same barrel for piezo sensor located at the same distance from chamber end produced somewhat variable results as compared to copper crusher results. The difference in chamber pressure in megapascal (MPa) ranges from minimum 5% for NSTD ammo to maximum 9.58% for NSTD ammo. Similarly, the difference in chamber pressure for piezo and copper crusher for NATO ammo ranges from 3.64% to 7.15%.

The deformation achieved via copper crusher varies nonlinearly as per theory and the same becomes more and more evident for higher values of pressure. The results for current research however do not show a clear difference between deformations which is conclusive enough for nonlinear behavior of copper material. However, clear higher values for chamber pressure have been noted for piezo sensor as compared to copper crusher for both types of fired ammos. Mean values of fired test series are given in Table 3.

The data obtained for chamber pressure through copper crusher and piezo sensor can also be critically analyzed for relative spread in peak pressure values as described by Coghe et al. [3]. The statistical equivalence of measurement techniques can also be easily compared via calculating relative spread in peak pressures at gun chamber.

Table 4 depicts an interesting result regarding peak pressure at chamber using copper crusher. The values of standard deviation by using standard NATO ammunition show a clear difference of measured pressure compared to nonstandard local ammunition. The values can be taken as an indication of unreliability of copper crusher measurement technique which is clearly affected by type of ammunition as well as other multiple factors. The values of relative spread also indicate same trend of copper crusher methodology depending on type of ammunition. The consistent trend in stable values of chamber pressure is clearly visible for standard NATO ammunition.

Table 5 shows chamber pressure measured at 25 mm using piezo sensor. The values of standard deviation and relative spread both strongly stress previous observation of stable and repeatable values for both ammunitions using piezo sensor. The lower trend of standard deviation irrespective of ammunition type is a strong endorsement of our initial assessment regarding accuracy of piezo sensor compared to copper crusher method.

The spread and standard deviation values from aforementioned tables for both copper crusher and piezo sensor clearly indicate stable and marginally repeatable values for piezo sensor due to lower values of standard deviation (SD) and relative spread.

After having comparative analysis of pressure results through copper crusher and piezoelectric transducer at 25 mm (NATO specified for chamber pressure vide drawing 6 in NATO MANUAL MOPI as shown in Figure 7), having observed that piezo pressure is more accurate, the case mouth pressure (at 54 mm from chamber end vide drawing b-35 in NATO MANUAL MOPI as shown in Figure 3) as specified in NATO EPVAT system (MOPI NATO 7.62 mm ammunition) is even more accurate and closer to true pressure. A number of firing results were obtained with the help of two different standard ammunitions' firing of ten rounds in each ammo test series. Mean values of fired test series are shown in Table 6.

The results for case mouth pressure at 54 mm from chamber end indicate a variable difference in pressure as compared to chamber pressure which ranges from 3.1% to maximum of 15.3% higher values of case mouth pressure. The higher values of piezo pressure for case mouth indicate a clear pattern of higher values for NATO ammo. The corresponding values of case mouth pressure for second category of NSTD ammo indicates lower values of measured pressure.

5. Simulation Tools for Crusher Material Modeling

In order to obtain accurate finite element modeling results, it is essential to implement material models in conformance with the actual copper behavior. As the exact material characteristics of copper crushers were not known, an experimental study was performed in order to obtain necessary parameters for a suitable material model. As the copper crusher application does not involve working under extremely high pressures, the material characterization was limited to the determination of a strength model [3]. Extensive use of plastic stress models in simulation has been found under high deformation and elevated temperature conditions [17]. Two different strength models were considered for the copper material of the crushers.

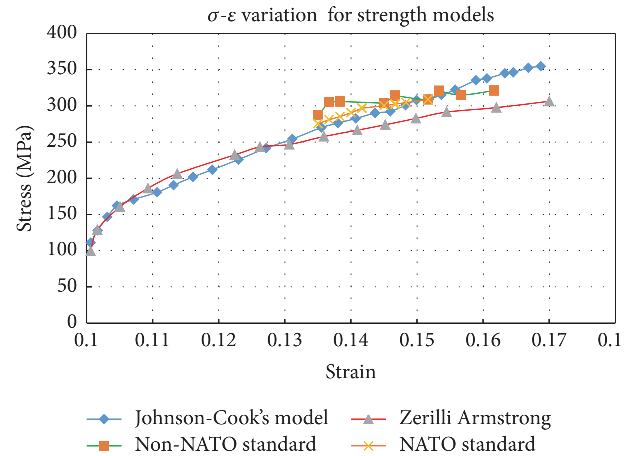

FIGURE 12: Curve fitting of experimental and model parameters.

The Zerilli-Armstrong model [5, 18] for face-centered cubic materials (FCC) like copper was given by

$$Y = A + C_0 \sqrt{\epsilon} e^{-C_1 + C_2 \ln \dot{\varepsilon}}. \quad (1)$$

The Johnson-Cook model [19] was developed to model the mechanical behavior of body-centered cubic materials (BCC), for example, steel, and declared as a very adaptable model which gives satisfactory results. Its mathematical expression is given by [5, 19] in

$$\sigma = \left(A + B\varepsilon_p^n\right)\left(1 + C \ln \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\left(1 - \frac{T - T_0{}^m}{T_m - T_0}\right), \quad (2)$$

where A, B, C, n, and m are the material parameters to be determined and $\dot{\varepsilon}$ is a reference strain rate (chosen as 1 per sec). T_m and T_0 are the melt temperature of the considered material and a reference temperature, respectively. Considering the melting temperature of pure copper, T_m was calculated as 1357 K, whereas, T_0 at room temperature was chosen as (294 K).

Figure 12 indicates the variation of σ-ε for copper which is nonlinear material. Analytical strength models Johnson-Cook and Zerilli-Armstrong have been compared with the results of real time copper crusher deformation. The results for both ammunitions (NATO standard and non-NATO standard) while using copper crusher show an agreement with Johnson-Cook model and hence, the same was used to get simulation results.

ANSYS workbench is used to carry out finite element analysis. The model is analyzed with real boundary conditions using Johnson-Cook model for copper material and a highly refined mesh. The pressure is applied mainly on the copper crusher to optimize the deformation with varying pressures. A fixture showing placement of copper crusher and piezoelectric transducer at chamber (25 mm from chamber end) is shown in Figures 13 and 11. Table 1 gives the components detail of Figure 11.

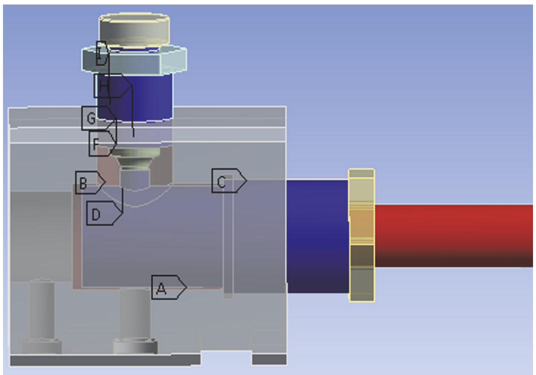

FIGURE 13: NATO proof barrel with copper crusher fixture.

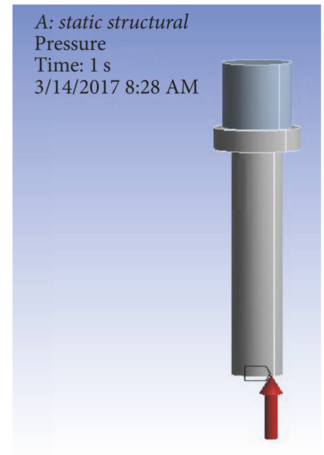

FIGURE 15: Applied pressure on copper crusher.

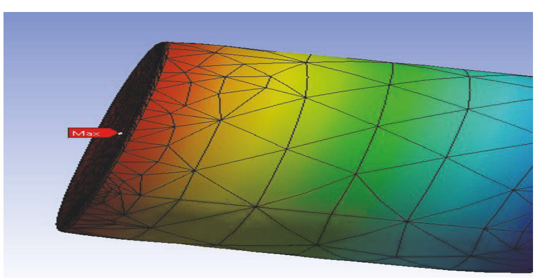

FIGURE 14: Refinement where max pressure occurs.

TABLE 1: Detail of labels used in Figure 11.

Label	Details
1	Thumb screw
2	Hollow nut
3	Copper crusher
4	Star washer
5	Piston
6	Piston guide
7	Brass sealing washer
8	Housing
9	Barrel locking sleeve
10	Barrel
11	Bolt head
12	Firing bolt
13	Bolt carrier
14	Firing pin
15	Barrel tightening nut

5.1. Meshing. To perform finite element analysis, our model is meshed such that the solution converges with more accuracy and real time results as shown in Figure 14. Refinement meshing is done on the regions of copper crusher chamber side to obtain and analyze the exact position from where the crusher deforms up to maximum limit.

5.2. Boundary Conditions for Copper Crusher. The material properties of copper are changed since copper crusher undergoes series of chemical processes from copper rod till miniature sized (4 mm × 6 mm) cylinders (copper rod, machining, blank, annealing, pickling, passivation, compression, and copper crushers finished product). Modulus of elasticity has been calculated through inverse numerical technique. The parameters used in the finite element analysis are as follows:

(i) Density = 8960 kg/m3 (constant value)

(ii) Modulus of elasticity = 1326 MPa (constant value)

(iii) Pressure = variable.

After setting up the constraints with certain mechanical material properties of pure copper crusher's density, ultimate tensile strength, yield strength, compressive strength, and modulus of elasticity. The model is simulated critically in 5 different scenarios and their corresponding deformation effects are shown in Figures 15–22.

5.2.1. Case 1

(i) Density = 8960 kg/m3

(ii) Modulus of elasticity = 1326 MPa

(iii) Pressure = 289.4 MPa

5.2.2. Case 2

(i) Density = 8960 kg/m3

(ii) Modulus of elasticity = 1326 MPa

(iii) Pressure = 296.9 MPa

Table 2: Experimental analysis of pressure at 25 mm copper crushers test.

Ammo test #	Mean of 10 fired rounds			
	Length of copper crusher		Deformation [mm]	Pressure [MPa]
	Before fire [mm]	After fire [mm]		
1-NATO	06	5.142	0.858	297.69
2-NATO		5.161	0.839	293.6
3-NATO		5.15	0.85	296.9
1-NSTD		5.148	0.852	296.24
2-NSTD		5.141	0.859	297.77
3-NSTD		5.126	0.874	300.93

Table 3: Comparative analysis of piezoelectric transducer and copper pressure at 25 mm.

Test ammo #	Mean of 10 fired rounds				
	Piezo pressure [MPa]	Copper crusher		Difference Piezo – copper	
		Deformation [mm]	Pressure [MPa]	[MPa]	%* A
1-NATO	317.28	0.858	297.69	19.59	6.17
2-NATO	316.2	0.839	293.6	22.6	7.15
3-NATO	308.125	0.85	296.9	11.22	3.64
1-NSTD	327.675	0.852	296.24	31.39	9.58
2-NSTD	319.305	0.859	297.77	21.53	6.74
3-NSTD	316.775	0.874	300.93	15.84	5.00

* A: percentage increased in piezo pressure with reference to copper crusher pressure.

Table 4: Standard deviation and relative spread using copper crusher method at 25 mm.

Test ammo #	Mean of 10 fired rounds				
	Chamber pressure [MPa]	Standard deviation [MPa]	Max value [MPa]	Min value [MPa]	Relative spread (%)
1-NATO	297.69	6.34	308.8	291.5	5.93
2-NATO	293.6	6.39	302.4	287.2	5.29
3-NATO	296.9	5.34	304.5	287.2	6.02
1-NSTD	296.24	9.80	321.2	287.2	11.83
2-NSTD	297.77	8.32	310.8	287.2	8.21
3-NSTD	300.93	11.81	321.2	287.2	11.83

Table 5: Standard deviation and relative spread using piezo pressure method at 25 mm.

Test ammo #	Mean of 10 fired rounds				
	Piezo pressure [MPa]	Standard deviation [MPa]	Max value [MPa]	Min value [MPa]	Relative spread (%)
1-NATO	317.28	4.73	326.8	310.95	5.09
2-NATO	316.2	3.75	322.7	309.55	4.24
3-NATO	308.125	4.54	317.8	304.3	4.43
1-NSTD	327.675	4.99	336.95	320.9	5.00
2-NSTD	319.305	5.50	326.25	307.5	6.09
3-NSTD	316.775	10.63	329.7	297.5	10.82

Table 6: Chamber pressure versus case mouth pressure.

Test ammo	Mean of 10 fired rounds (chamber versus case mouth) Piezo pressure at 25 mm (chamber) [MPa]	54 mm (case mouth) [MPa]	% increase in *CMP w.r.t. chamber [%]
1-NATO	317.28	356.105	11.02
2-NATO	316.2	364.59	15.3
3-NATO	308.125	356.28	11.27
1-NSTD	327.675	337.83	3.1
2-NSTD	319.305	332.79	3.6
3-NSTD	316.775	335.53	4.71

*CMP: case mouth pressure.

Table 7: Cost benefit analysis (CBA).

(a)	Number of copper crushers used in proof firing during year 2012/13 (excluding production rejection)	15,400 crushers
(b)	Number of copper crushers used in proof firing during year 2013/14 (excluding production rejection)	13,582 crushers
(c)	Number of copper crushers used in proof firing during years 2012/13 & 2013/14 (excluding production rejection)	28,982 crushers
(d)	Cost of one radial copper crusher (4 × 6 mm)	2.96 USD
(e)	*Total cost of crushers used in two years*	*85,786.72 USD*
(f)	*Cost of one piezoelectric transducer*	*9,548 USD*
(g)	*Cost comparison between piezoelectric and copper crushers in two years*	*1 : 8.98424*
(h)	Saving (difference of cost in two years' proofing if piezo method is adopted)	76,241 USD
(i)	*Approx. average saving per year*	*≈38,120 USD*

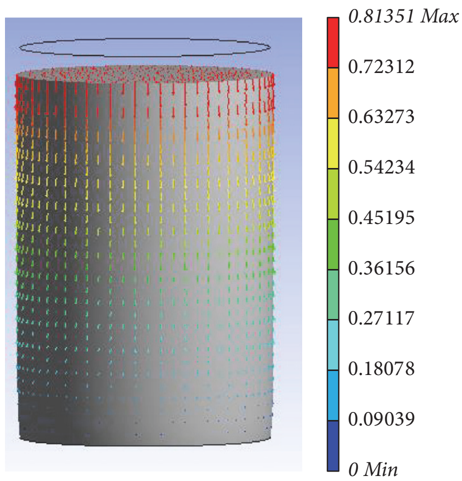

Figure 16: Linear deformation obtained.

5.2.3. Case 3

(i) Density = 8960 kg/m3

(ii) Modulus of elasticity = 1326 MPa

(iii) Pressure = 300.2 MPa

5.2.4. Case 4

(i) Density = 8960 kg/m3

(ii) Modulus of elasticity = 1326 MPa

(iii) Pressure = 304.5 MPa

5.2.5. Case 5

(i) Density = 8960 kg/m3

(ii) Modulus of elasticity = 1326 MPa

(iii) Pressure = 310.8 MPa

6. Cost Benefit Analysis

Copper crusher is used one time only as it is deformed during firing and has to be replaced for every subsequent fire. However, in case of piezoelectric transducer, a sensor once installed is used for a lifetime. In order to have a comparative analysis between copper crushers and piezoelectric transducer, cost of copper crushers used in two years during proof firing of 7.62 × 51 mm ammunition is compared with one piezoelectric transducer (considering warranty period of two years). The cost benefit analysis carried out for actual consumption of copper crushers during the last two years with piezoelectric transducer is shown in Table 7.

7. Results Validation through Simulations

In order to validate pressure values obtained from copper crushers through series of real time firing of ammunition, the pressure obtained through deformation of copper crusher was taken as reference and validated through ANSYS workbench. Comparative analysis on experimental and simulation results was carried out to validate experimental data by using a sample size of 10% test round results of a batch of 50 rounds. The same shows an encouraging agreement between values as the deformation achieved in simulation results is

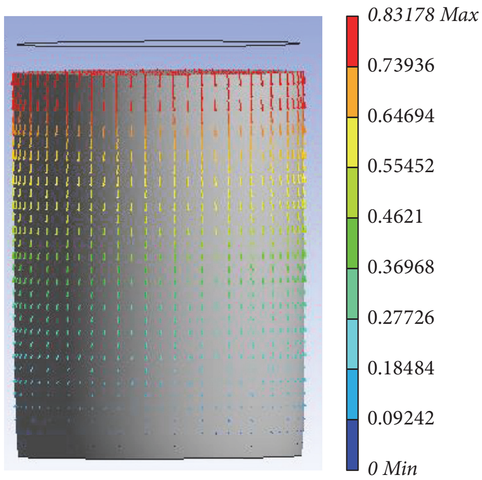

Figure 17: Linear deformation obtained.

Figure 18: Applied pressure on crusher.

approximately the same as was actually achieved in proof firing via copper crusher. The values of peak pressure as converted from deformation of copper material using Terage tables were applied as load in simulation to check whether the same deformation is achieved through simulation. A close agreement of both deformation values is given in Figure 23.

Table 8 indicates the same comparative data in tabular form. The minor differences between two results are possibly due to the fact that few material properties were either assumed or unknown due to limited material property data from supplier.

8. Discussion

8.1. Discussion on Chamber Pressure Measurement. The comparison of results for non-NATO standard (NSTD) ammunition of local origin unveils clear flaws of copper crusher methodology in measuring chamber pressure. Figure 24

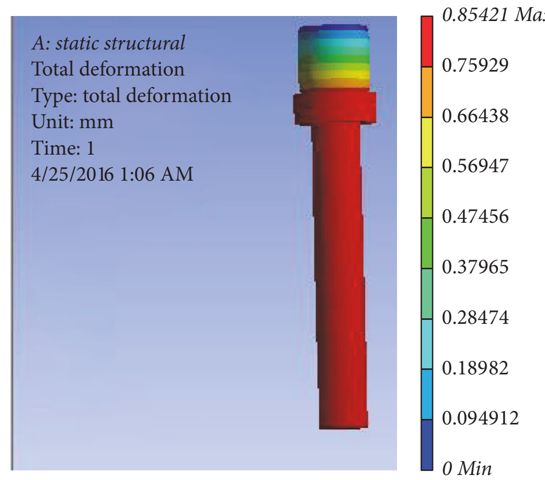

Figure 19: Linear deformation obtained.

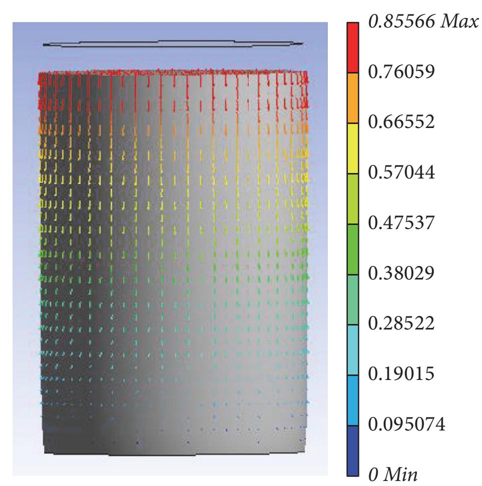

Figure 20: Linear deformation obtained.

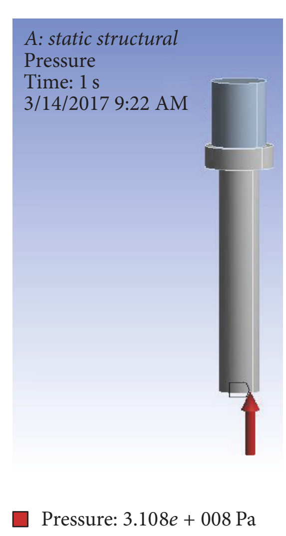

Figure 21: Applied pressure on crusher.

Table 8: Pressure results validation on ANSYS ® workbench.

Real time firing results obtained by copper crushers (original length = 6.0 mm)		Simulation results on copper crusher (6.0 mm) using ANSYS	
Deformation noted [mm]	Pressure obtained [MPa]	Applied pressure [MPa]	Deformation obtained [mm]
0.82	289.4	289.4	0.8135
0.85	296.9	296.9	0.8318
0.87	300.2	300.2	0.8542
0.89	304.5	304.5	0.8556
0.92	310.8	310.8	0.8734

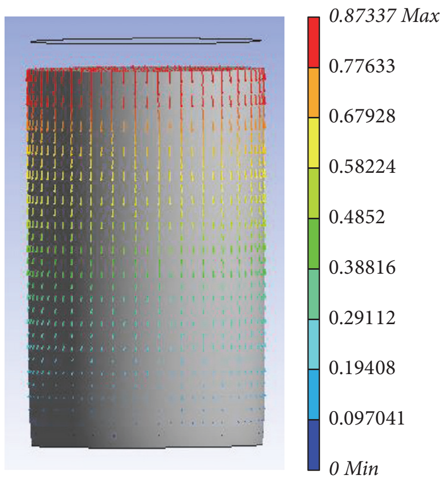

Figure 22: Linear deformation obtained.

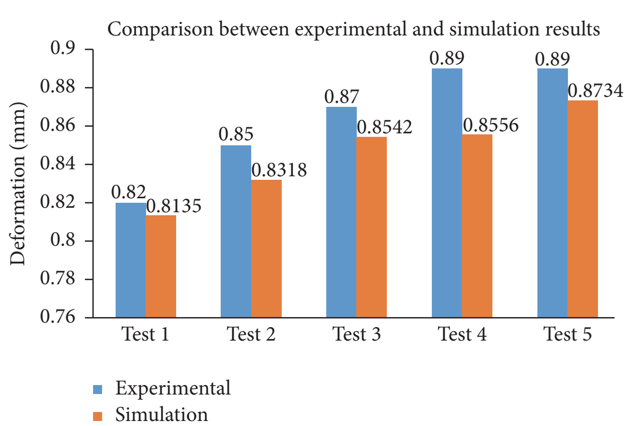

Figure 23: Comparison of experimental and simulation deformations.

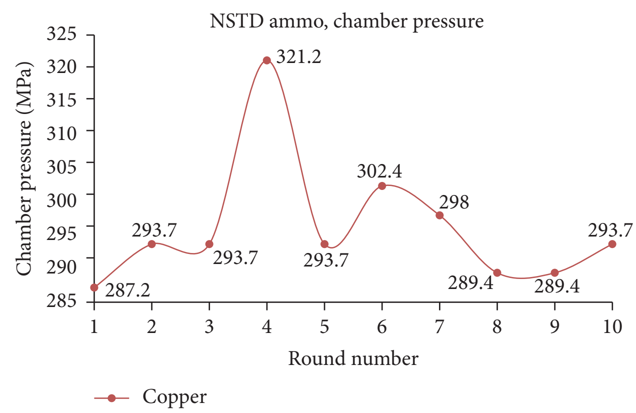

Figure 24: Chamber pressure measured with copper crusher using NSTD ammunition.

highlights a major difference in pressure between different NSTD rounds fired to measure chamber pressure via copper crusher and thus endorsing nonsuitability of method for sensitive applications. The chamber pressure results for various rounds vary from 287.2 MPa to highest 321.2 MPa and thus an erratic nature of more than 10% for NSTD ammunition is recorded. It could be further stated from test to test as there are numerous factors which come into play when using copper crusher as measurement technique.

The comparison between copper crusher and piezo sensor for chamber pressure values indicates another fact that copper crusher values for the same ammunition and simultaneous measurement with piezo sensor are not only erratic in nature but also on the lower side which validates our initial assumption of nonsuitability of copper crusher measurements. The comparison between copper crusher and piezo sensor for chamber pressure values indicates another fact that copper crusher values for the same ammunition and simultaneous measurement with piezo sensor are not only erratic in nature but also on the lower side which validates our initial assumption of nonsuitability of copper crusher measurements. The same has already been reported by Coghe et al. [3] where lower peak pressures have been observed for different caliber ammunition using copper crusher. The corresponding values from piezo sensor however are reported to be higher for the same ammunition. The same is on lower side as compared to true pressure due to presumable nonlinear deformation of copper material. Hence, the results obtained for nonstandard ammo clearly indicate a close agreement with existing observations that copper crusher technique does not present true barrel pressure. The results by piezo sensor on the contrary indicate a more smooth pattern of chamber pressure from round to round and erratic nature of results is nonevident as it was for copper crusher

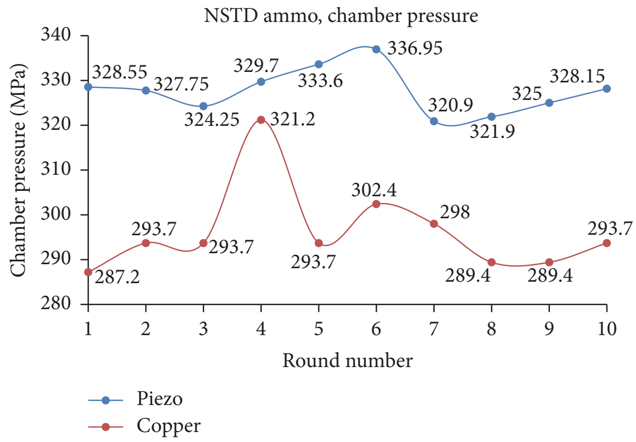

Figure 25: Comparison of chamber pressure measured with copper crusher and piezo sensor simultaneously using nonstandard ammunition.

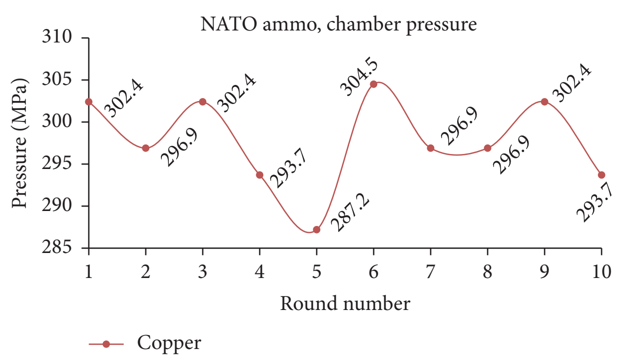

Figure 26: Chamber pressure measured with copper crusher using standard NATO ammunition.

results. Figure 25 presents a broad view of first series of proof fire using nonstandard ammunition to measure chamber pressure by both piezo sensor and copper crusher within the same barrel.

The results when extended to change of ammunition, from NSTD to NATO ammo, did not indicate any difference with regard to results as compared to nonstandard ammunition. The copper crusher method produced the same erratic nature of results for chamber pressure irrespective of ammunition. The copper crusher method produced the same erratic nature of results for chamber pressure irrespective of ammo type which is in agreement with existing research outlines by Kuokkala et al. [11]. However, for standard NATO ammo, comparatively higher values of chamber pressure have been recorded by copper crusher. The results are consistent from test series 1 to test series 3 for standard NATO ammo.

The values of chamber pressure by copper crusher using NATO ammo are presented in Figure 26. In order to judge the effect of ammunition type on chamber pressure measurement technique and the chamber pressure results for standard ammunition using both copper crusher and piezo sensor, an endorsement of previous finding is found; that is, piezo sensor method records higher pressure values as compared to copper

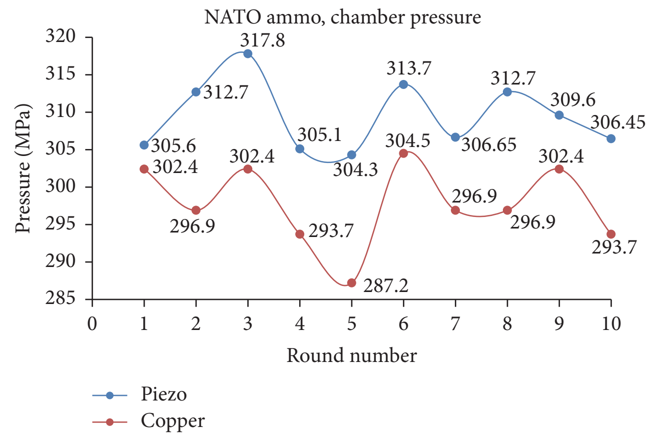

Figure 27: Chamber pressure measured with copper crusher and piezo sensor simultaneously using standard NATO ammunition.

crusher. The copper crusher on the other hand presents lower values of chamber pressure for the same experiment and the same standard ammo. It coincides with existing research output by Kuokkala et al. [11] who claim to have observed beyond 20% higher values in piezo sensor compared to copper crusher pressure values. The result remains consistent for three series of fires using NATO ammunition. The results obtained for standard ammunition once again stress the fact that copper crusher irrespective of ammunition type does not present true chamber pressure. Figure 27 presents a comparison of two measurement techniques installed simultaneously in a barrel using standard NATO rounds.

8.2. Discussion on Case Mouth Pressure Measurement. Case mouth pressure was measured using piezo sensor only as installation of copper crusher to measure the same is not possible. Furthermore, piezo sensor method for case mouth pressure presents even a simpler installation as compared to chamber pressure as no drilling in this case is required. The following results have been categorized as NSTD ammunition and NATO standard ammunition using piezo sensor.

The NSTD ammunition results for case mouth pressure as measured in three different test series indicate consistent pressure values from series 1 to series 3. Piezo sensor case mouth pressure values indicate smoother pattern even with NSTD ammunition. Figure 28 indicates different test series results for piezo sensor installed at case mouth position.

Case mouth pressure measurement using standard NATO ammunition with piezo sensor is also investigated for effect of ammunition type. The results present close agreement with previous discussions about piezo sensor method as reliable and consistent as compared to copper crusher method irrespective of ammo type. The result however indicates a close consistency in result for case mouth pressure and somewhat marginally deviates from round to round. Figure 29 presents three test series of fires for standard NATO ammunition.

8.3. Discussion on Simulation Results. With the help of reverse numerical technique, chamber pressure obtained

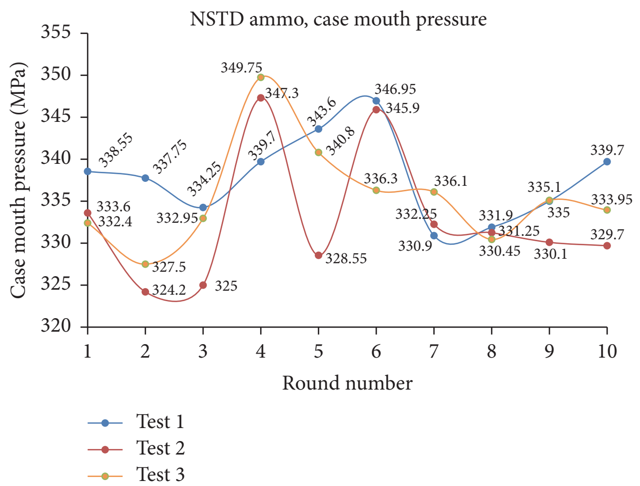

Figure 28: Case mouth pressure measured with piezo sensor using nonstandard ammunition.

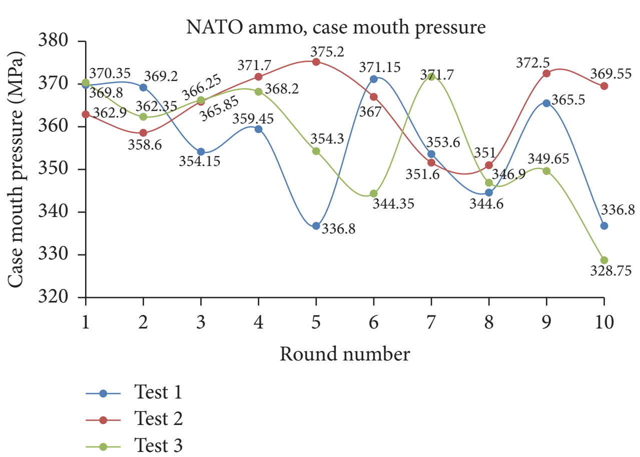

Figure 29: Case mouth pressure measured with piezo sensor using standard NATO ammunition.

through deformation of copper crusher was applied on copper crusher using ANSYS workbench to validate corresponding deformation, thus confirming results. On the basis of experimental and simulated results the following points are highlighted:

(i) The variation in pressure between piezoelectric sensor and copper crushers has been observed as 5–10%.

(ii) No significant difference in results of standard ammunition (NATO) and nonstandard (NSTD) ammunition is observed. Significant difference in CMP versus chamber pressure has been observed in case of NATO ball ammunition with 11–15% variation as compared to nonstandard ammunition.

(iii) It is a well-established fact that ANSYS is a very useful simulation tool for the validation of real time firing results (pressure values against deformation of copper crusher).

9. Conclusions

Based on experimental and numerical analysis, it is evident that the piezo pressure observed is higher (closer to true pressure) than copper crusher pressure at 25 mm distance from chamber end. Therefore, piezo pressure is more accurate and reliable to ensure effective ammunition proofing and due safety of weapon.

The results further reveal that the pressures recorded by piezo transducers are slightly higher compared to copper crusher pressure irrespective of the type of ammunition. The ammo of both categories revealed close agreement of persistent higher pressure values for piezo as compared to copper crusher. The same results have been validated by simulation and a close settlement between deformations is achieved through real time firing and simulation has been found, validating experimental results.

The results in current work indicate that copper crusher pressure and piezo pressure have close agreement at lower pressures and the same is not true for higher values of pressure due to nonlinear deformation of crusher material. Similarly, the pressure observed through EPVAT system at case mouth is even more accurate and closer to true pressure. Hence, the proofing of ammunition with NATO EPVAT system should be adopted instead of obsolete and unreliable pressure measuring by copper crusher method.

The confirmation of reliability and repeatability of results for piezo sensor method is also evident through standard deviation and relative spread values. Close agreement between values obtained for chamber pressure through piezo sensor with lower values of standard deviation and relative spread is conclusive enough for initial argument of piezo sensor being superior compared to copper crusher method.

The cost benefit analysis for a year of proofing clearly indicates a wide difference of financial impact if piezo sensor instead of conventional copper crusher method is adopted. The accuracy, repeatability, and reliability of ballistic results through EPVAT system supersede conventional and high variable method of ballistic measurement through copper crusher.

10. Recommendations

The analysis shows that, due to accuracy, cost, and quick results, piezoelectric transducers have an edge over copper crushers. This change in methodology will increase the acceptability of the product worldwide thus bringing it to the NATO standard. The ease of installation and automatic generation of ballistic parameters unlike copper crusher provides ammunition manufacturers and proofing personnel with an added advantage at a considerably lower cost. The accommodation of piezoelectric sensor method of ballistic measurement will enhance our capability to produce international quality standard ammunition and weapons. It is highly recommended that standard NATO ammunition should be manufactured and its testing be done by using EPVAT method of proof testing to ensure international quality, capturing customer satisfaction and thus reaching new markets.

Nomenclature

Abbreviations

A:	Yield strength, MPa
AVL:	Copper manufacturer, AVL Technology Inc.
B:	Hardening modulus, MPa
BDMS:	Ballistic Data Measurement System
C:	Strain rate sensitivity coefficient
CIP:	Permanent International Commission
CMP:	Case mouth pressure
C_0, C_2, C_3, C_4:	The material parameters
EPVAT:	Electronic Pressure, Velocity, and Action Time
M:	Thermal softening coefficient
MOPI:	Manual of Proof and Inspection
N:	Material constant
NATO:	North Atlantic Treaty Organization
NSTD:	Non-NATO standard
SAAMI:	Sporting Arms and Ammunition Manufacturers' Institute
T:	Temperature
US:	United States
USD:	Dollars (United States of America)
w.r.t.:	With reference to.

Units

ft./s:	Feet per second
g/cm3:	Gram per centimeter cube
J:	Joules
Mm:	Millimeters
MPa:	Megapascal.

Symbols

Σ:	The stress, MPa
p:	The plastic strain
Έ:	The strain rate.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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