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Highlights

A concise review on degradation of gun barrels and its health monitoring techniques

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Deepak Kumar, Sahil Kalra, Mayank Shekhar Jha*

- Various causes of the failure of Gun barrels are reviewed which results into high residual stresses, crack growth followed by failure of the barrels.
- Autofrettage process is described using FEA which reduce the residual stresses on the barrel.
- Effect of wear, corrosion, and thermal fatigue on Gun barrels life is discussed in detail.
- Diagnostics passive and active instruments are discussed in detail.
- Prognostic techniques are discussed in detail to predict the remaining useful life of the barrels.

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Review

A concise review on degradation of gun barrels and its health monitoring techniques

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ABSTRACT

Unpredicted failure of barrels is a common problem for cannons, artilleries, and other ballistic missiles. The major cause of the barrels' failure is high pressure, which generates large residual stresses in the inner layers of the barrel. To reduce the stresses, autofrettage of the barrels is carried out in which the core material is allowed to deform plastically and the upper layers produce a continuous elastic force over the inner layers. Autofrettage is a common engineering practice which is carried out while manufacturing of barrels to increase the operational life significantly. The other reason for barrel failure is material degradation which occurs due to thermal fluctuations, fatigue, wear, erosion, corrosion, etc. In order to correlate them with the life of the gun barrels, various tools such as borescope, variety of gauges, optical bore-mapping, ultrasonic sensors, and diamond indenter-based instruments are used. The measured data is then used to formulate the empirical mathematical relation which is further used to calculate the remaining useful life of the barrels. The other mathematical models are the prognostics models which are generally Probabilistic models or Data-driven models (such as machine learning) or Hybrid models. By using these models, we estimate the remaining life of barrels by using any of the techniques such as heat emission method, dimension increment method, muzzle velocity method, and strain-based methods. The paper concisely summarize various techniques used for diagnostic and prognostic of barrels to estimate the degradation profile and to calculate the remaining useful life (RUL).

1. Introduction

Ammunition is a defense material projected against a predefined target. These materials are covered with a casing made up of metals or alloys that are launched using a mechanical system. The launch system consists of two prime components- (i) combustion chamber, and (ii) barrel. The geometry of the combustion chamber and barrel is calculated depending on the range of a target. For example, large-caliber cannons are used to launch explosives to a long distance and may fire hundreds of rounds per minute. The performance, reliability, and service life of each of these components depend on mechanical properties, the strength of materials, design, and manufacturing processes.

In weaponry systems, barrels play a vital role by guiding the ammunition through a long and narrow cylindrical tube. The inner section of the tube is branched into three distinct regions starting from the breech face- combustion chamber, bore, and the muzzle. A typical design of a gun barrel with components like breech, bore, muzzle, etc. is illustrated in Fig. 1. The Fig. 1 shows the cut-section view of a gun barrel along with the cross-section view where the grooves are shown in the inner surface of the bore.

The outer diameter of the projectile (ammunition) is designed slightly smaller than the inner diameter of the cylindrical tube (barrel). During trigger, the propellant which is generally the chemical substance burns out and produces a large amount of gases. The gases consequently build a high pressure which adds up with the mechanical force and increases the kinetic energy of the ammunition. This force pushes the ammunition towards the bore and muzzle of the barrel. The conversion of chemical to mechanical energy builds up high pressure and high temperature conditions inside the chamber. This causes erosion and wear of material after every subsequent firing (blast cycle), resulting into plastic deformation followed by permanent failure of the barrels [1]. The overall

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Nomenclature

A, B, C	Material constants
D_1, D_2, D_3, D_4, D_5	Material failure constants
L	Length of travel
M	Central ballistic parameter
m, n	Material constants
m_c	Charge mass
m_p	Projectile mass
P	Maximum pressure
p_i	Internal pressure
p_0	External pressure
r_i	Inner radius
r_0	Outer radius
T	Actual temperature
T_r	Room temperature
T_m	Melting temperature
V, v_{mz}	Muzzle velocity
W,w	Erosion rate
PF	Propellant Factor
CF	Coolant Factor
Δ	Loading density
ε	Effective plastic strain
$\dot{\varepsilon}$	Effective plastic strain rate
$\dot{\varepsilon}_0$	Reference strain rate
Λ	Specific force
Φ	Volume fraction
σ^*	Stress triaxiality
σ_r	Radial stress
σ_θ	Circumferential (hoop) stress
σ_y	Yield stress

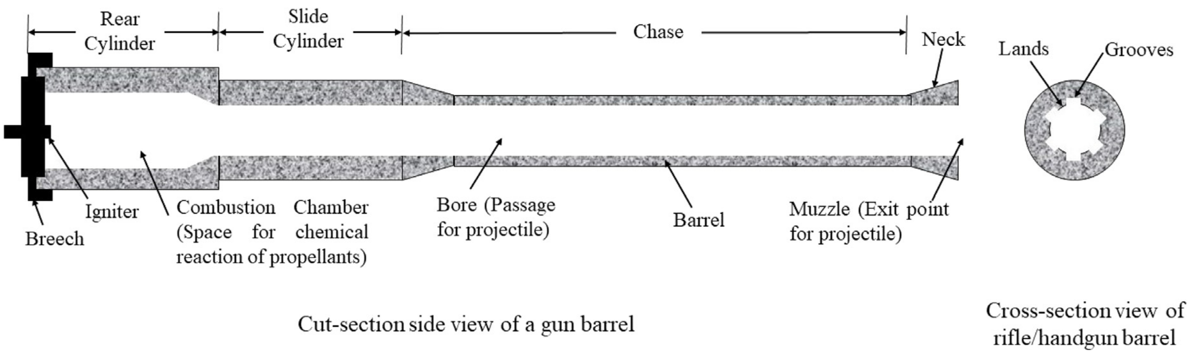


Fig. 1. Typical design and components of a gun barrel.

rate of wear and erosion depends upon the type of gases released, temperature, pressure, flow rate and the number of ballistic cycles that occurred through it [2,3]. The effects of individual factors on the overall life of a barrel are explained in the following sections.

2. Reasons for life degradation in the gun barrels

The life degradation of barrels occurs due to the following reasons: (i) generation of reactive gases (Fig. 2), (ii) thermal fatigue, and (iii) residual stresses.

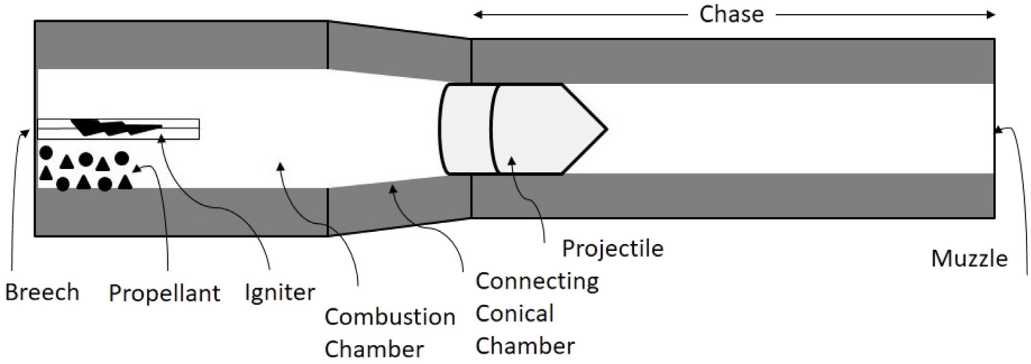


Fig. 2. Firing of a projectile through barrel.

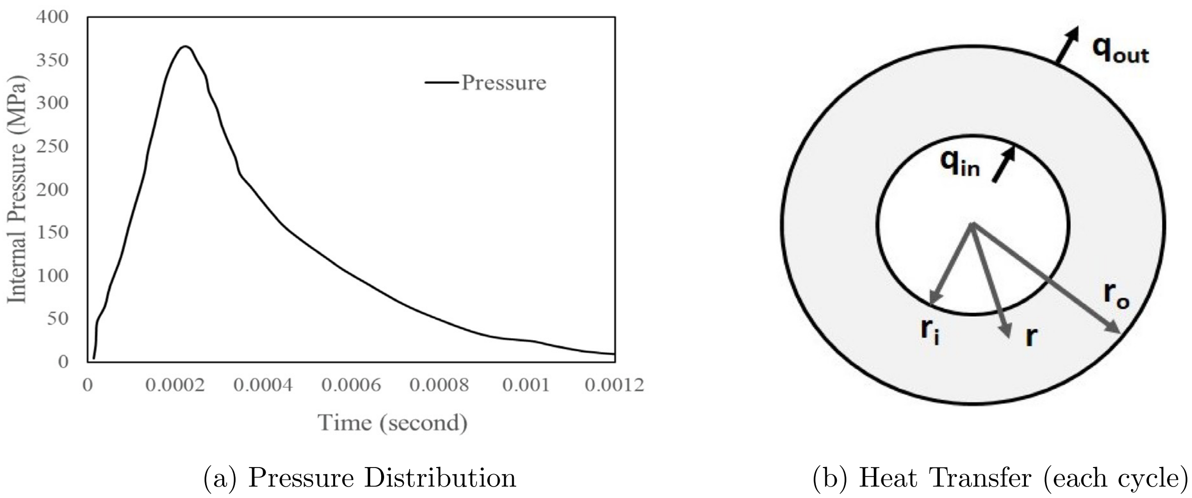


Fig. 3. Schematic of pressure and heat transfer to the gun barrel after each firing.

- **Reactive gases** — During the combustion of chemicals, various gases are released inside the chamber (CO, CO_2, H_2, H_2O and N_2). These gases form a chemically-affected zone or layer (CAZ/CAL) with thickness of the order of one to ten microns [4,5]. The zone is also referred to as white-layer. The layer penetrates inside the cracks and increases the surface wear rate [6]. The analysis of study done by *J Kimura* [7] shows that the relative contribution of these chemicals to erosion rate can be listed in the following sequence:

  $CO_2 > CO > H_2O > H_2 > 0 > N_2$

  where N_2 has negative resistive influence i.e. it has chemically protective property.
- **High pressure** — During the combustion process, the maximum pressure inside the combustion chamber reaches the level of 600 MPa. The maximum pressure is reached within a millisecond in almost all guns as shown in Fig. 3(a). The Fig. 3(a) shows pressure vs. time curve for a shotgun [8,9]. The curve is steeper at the beginning of the cycle as compared to the end which denotes that the peak pressure is attained within a few milliseconds of combustion, and then decreases rapidly. Due to this high pressure, the resultant stresses inside the chamber cross the yield limit of the barrel material. It causes permanent bore expansion. In severe cases, the failure in the brittle gun barrel occurs due to sudden bursting. However, in the ductile barrels, it occurs as crack propagation resulting in leakage of propellant gases. It should also be understood that the gun performance varies with barrel length and the type of firing action.
- **Thermal fatigue** — As soon as the projectile is fired, the bore surface temperature reaches around 1100–1200 °C. However, at the end of the barrel (towards the muzzle) the temperature is almost half in magnitude which causes a temperature gradient generated within the barrel body. Repeated cooling and heating cycles create a heat-affected zone which influences the overall life of the gun barrel [10–12]. Fig. 3(b) shows the cross-section of a thick tube of a gun barrel in which heat is generated at the inner surface and heat loss occurs at the outer surface through convection and radiation. During the process of combustion, a very large amount of heat is transferred to the gun bore surface (at r_i) in a few milliseconds. Subsequently, heat penetrates

into the gun barrel material (by r) and requires some time to reach the outside surface (at r_o). q_{out} is composed of convection heat transfer (q_{conv}) and very small amount of radiation heat transfer (q_{rad}).

- **Coupled thermal loading and mechanical stress** — Temperature fluctuation causes thermal compressive stresses and residual tensile stress during alternate heating and cooling cycles, respectively. Zheng et al. [13] mentioned three kinds of stresses which are produced during firing- (i) mechanical stress which occurs due to the burning of chemical substances, (ii) thermal stress which occurs due to the temperature fluctuation during the heating cycle, and (iii) residual tensile stress which is caused after the firing. During the firing process, another couple of stresses exist- (a) shear stress caused by the combustion gases, and (b) contact stress by friction between the rotating band of a projectile and the gun bore surface. These two stresses cause thermo-mechanical fatigue (TMF) of the gun barrel. TMF causes fatigue cracks whose depth and size keep on increasing with subsequent firings.

2.1. Defects — Cause and control

In addition to the reasons discussed above, bore surface wear is another major cause of failure of the gun barrels. The barrels wear out because of two main causes- (i) erosion, and (ii) corrosion, which occurs at high temperature and pressure [14]. After repeated cycles of usage, the inner bore diameter tends to increase due to surface wear. The permissible bore wear is about 0.5%–1% for tank guns which need to be very accurate whereas it is about 5%–8% for indirect fire weapons like howitzers. Generally, the wear rates vary between 0.1 to 200 μm per round which can be minimized by using additives.

- **Erosion** — Erosion in weapons is defined as the gradual damage or enlargement of the bore surface as a result of bullet–barrel interaction after each firing. Research work on the barrel erosion mechanism dates back to the early decades of the 1900s [15–17]. Based on different causes of erosion, it has been categorized as chemical, thermal and mechanical erosion which are linked to each other [18,19]. Turley et al. [20] explained that the temperature of the inner chamber plays a significant role in the erosion process. The propellant gas elements such as oxygen and carbon react with the bore wall material and form oxide (FeO) and carbide (Fe_3C) layers on the barrel's inner surface. Shelton et al. [21] have studied about erosion phenomenon in gun barrels in reference to the heat transfer aspects. Bracuti [22] listed out a few effects of eroded bore surface: loss in firing range and range accuracy, loss in directional stability, reduction in barrel fatigue life, etc. One of the earliest methods used for the control of gun barrel wear is to increase the heat resistance of the bore surface by reducing the rate of heat transfer to the bore [23]. Brosseau and Ward [24–26] suggested wear-reducing additives such as polyurethane foam, titanium dioxide, and talc/wax which works on the phenomenon of reduction in heat transfer to the gun barrel. Fan and Gao [27] have reviewed additive materials used for erosion reduction and extension of barrel life. In order to protect the gun barrel surface from wearing off, Ahmad [28] suggested the use of erosion-resistant coating of the materials which have a high melting point, high hardness, low coefficient of friction, and thermo-chemical inertness. In this regard, Hammond [29] and Ebihara [30] did experiments with the chromium-plated gun barrels and reported a significant reduction in the erosion.
- **Corrosion** — Corrosion in metallic materials occur as a result of reaction among surrounding atmosphere with the temperature fluctuation and static/dynamic mechanical processes [31–34]. Hot corrosion is the term used for accelerated corrosion which increases the gun barrel wear at a faster rate and shortens its lifetime. In the early studies related to gun barrel wear, Zimmer and Haukland [35] have discussed the chemical reaction of carbon monoxide (CO) with iron (Fe) and alloying components such as chromium (Cr) or nickel (Ni). The reaction forms carbonyls like $Fe(CO)_4$ which causes corrosion. To prevent such wear action a mixture of wax and TiO_2 based additive are used which oxidizes the CO and minimizes the corrosion-affected barrel wear.

$$3TiO_2 + CO \rightleftharpoons T_3O_4 + CO_2 \tag{1}$$

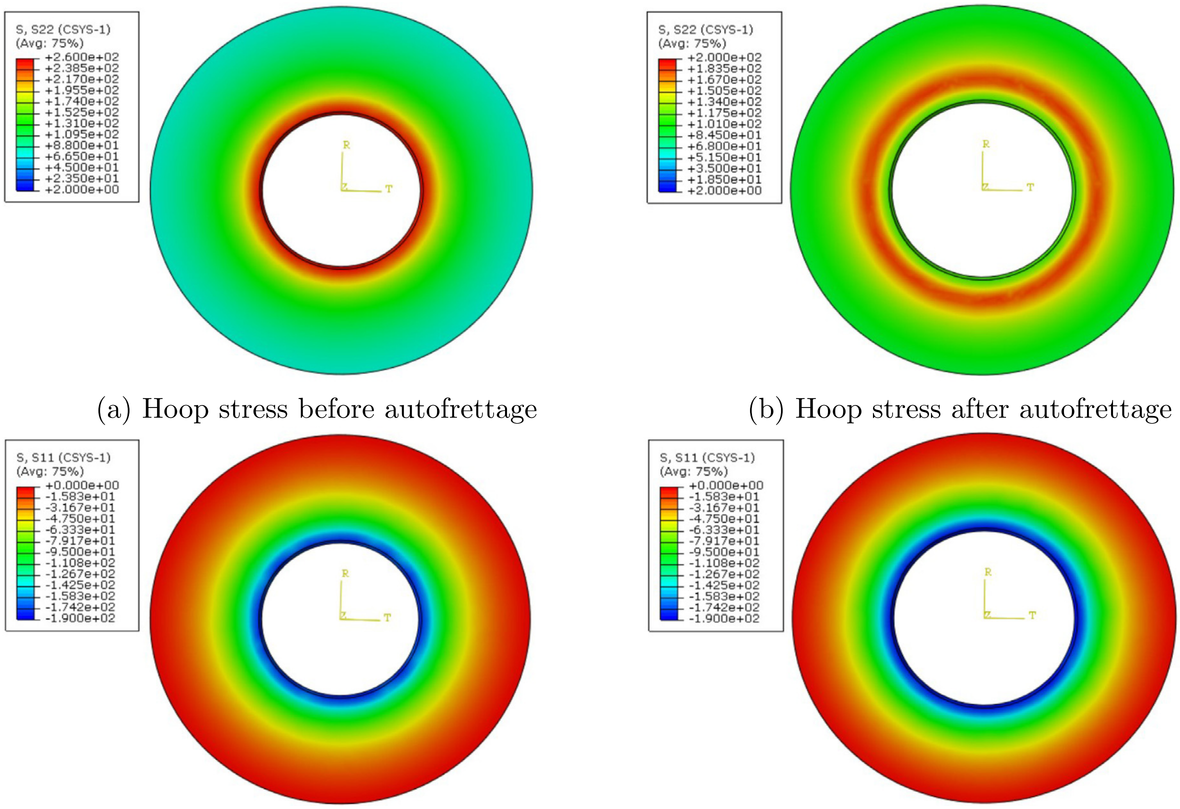
  Table 1 compiles various erosion reducing additive materials (ERAMs) which are experimentally suggested by researchers for erosion control in gun barrels.
- **Residual stresses** — Due to the generation of gases at high pressure, the barrels have to undergo axial, radial, and hoop stresses along the cross-section [43]. It has been observed that during the blast process, the high pressure creates tensile stress at the bore region making the resultant stress to be greater than the yield stress. This causes a plastic deformation at the inner layer, causing the upper layer to generate residual compressive stress on the inner layer.

  In order to have a clear understanding of the stress distribution in a gun barrel, a simulation work for a cylindrical tube subjected to an internal pressure is carried out in Abaqus software. The gun material is taken as steel which has yield strength of 270 MPa. We have set inner radius of 0.002 m, and outer radius of 0.005 m. The value of applied internal pressure is 200 MPa, which is less than the yield strength. The results show that the radial stress is compressive, whereas the hoop stress is tensile in nature. Also, magnitude of the hoop stress is much larger than that of the radial stress, which agrees with the study of Harvey [44]. Further, the hoop stress is maximum at the bore, and it reduces to a minimum non-zero value at the outer surface. On the other hand, the radial stress has a maximum value at the bore and is zero at outer surface (Figs. 4, 6).

To attain uniformly distributed stresses along the thickness of the gun barrels, they are subjected to the process of autofrettage in which the gun barrels are pressurized internally such that the material near the bore starts to yield, while the outer material remains in the elastic region. After release of internal pressure, the outer layers of material compress the inner layers thus generating a compressive residual stress in the zone near the bore.

Table 1
List of erosion reducing additive materials (ERAMs).

ERAMs	Effect	Reference
Polyurethane foam	The lifespan of M68 105 mm tank gun barrels increased 4-folds (from 100 to 400 rounds)	Joseph [36]
TiO_2-paraffin (45% + 55%)	It increased the total number of permissible rounds from 100 to 900 rounds	Katz [37], Lenchitz et al. [38]
Talc-paraffin (46% + 53.5%)	Erosion reduction is better compared to the TiO_2-paraffin, but, it formed residues on the bore surface	Picard and Trask [39], Picard [40]
Multifunctional ERAM composed of inorganic salts	Erosion-reducing performance of the salts (from high to low): $KHCO_3 > NH_4HCO_3 > (NH_4)_2 > CO_3 > K_2CO_3 > K_2NO_3 > K_2SO_4$	Bracuti et al. [41]
WS_2 nanoparticles	Solid lubricants for wear protection	Rezgui et al. [42]



(a) Hoop stress before autofrettage (b) Hoop stress after autofrettage

(c) Radial stress before autofrettage (d) Radial stress after autofrettage

Fig. 4. Stress distribution in a cylindrical gun tube before and after autofrettage.

In order to bring out the effect of this phenomenon, simulation results are obtained by finite element analysis on the same Abaqus model of the cylindrical tube. Now, the tube is autofrettaged at pressure values varying from below the yield point to above it. Here, the pressure range used for this purpose is 240–380 MPa. The von-Mises stress distribution shows that the stresses are more equitably distributed along the thickness of the autofrettaged cylinder (Fig. 5).

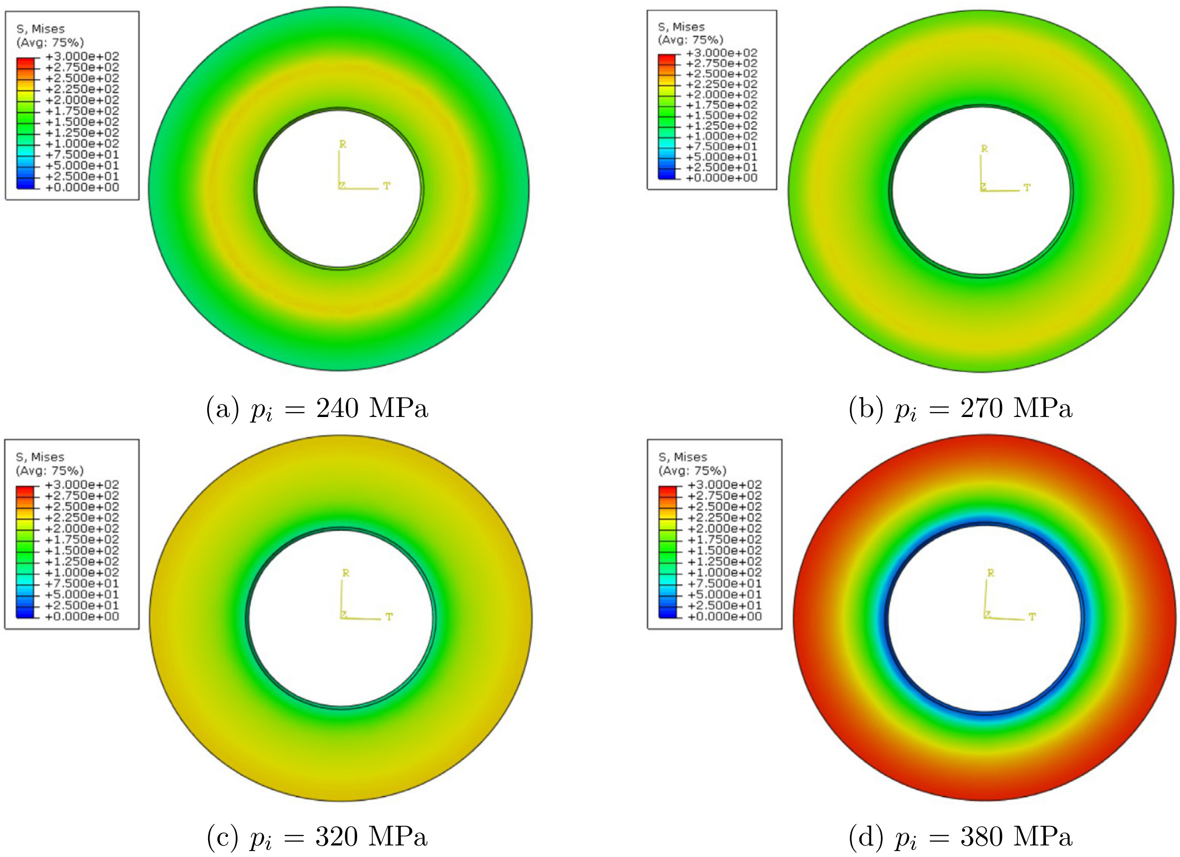


Fig. 5. Von-Mises stress distribution in gun barrel at various autofrettage pressure.

2.1.1. Mathematical comparison of stresses before and after autofrettage

Lame formulation gives the equation for relation of stress distribution in the direction of radial (σ_r) and hoop stress (σ_θ) [45,46].

$$\begin{aligned}\sigma_r &= \frac{r_i^2 p_i - r_o^2 p_o}{r_o^2 - r_i^2} - \frac{\left(p_i - p_o\right) r_i^2 r_o^2}{r^2\left(r_o^2 - r_i^2\right)} \\ \sigma_\theta &= \frac{r_i^2 p_i - r_o^2 p_o}{r_o^2 - r_i^2} + \frac{\left(p_i - p_o\right) r_i^2 r_o^2}{r^2\left(r_o^2 - r_i^2\right)}\end{aligned} \tag{2}$$

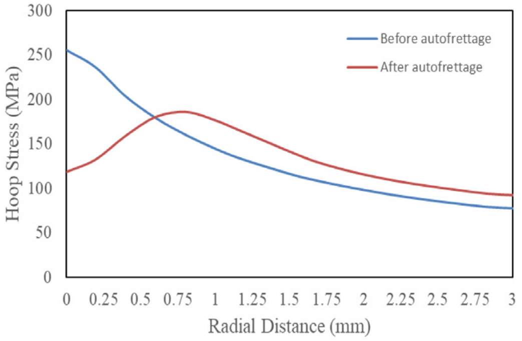
Before autofrettage, for simplification, setting external pressure value equal to zero ($p_o = 0$) we get following equations for stress distribution:

$$\begin{aligned}\sigma_r &= \frac{r_i^2 p_i}{r_o^2 - r_i^2}\left(1 - \frac{r_o^2}{r_i^2}\right) \\ \sigma_\theta &= \frac{r_i^2 p_i}{r_o^2 - r_i^2}\left(1 + \frac{r_o^2}{r_i^2}\right)\end{aligned} \tag{3}$$

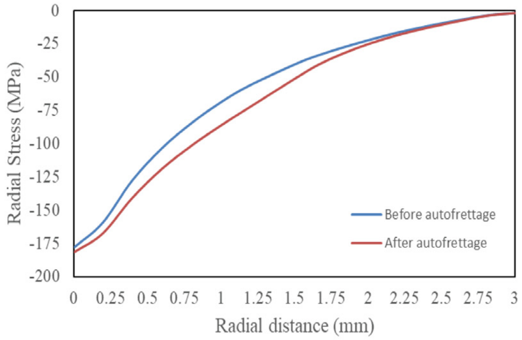
In the above equations it can be observed that radial stress is always negative and hence compressive, and the hoop stress is always positive and hence tensile. Numerically, the value of hoop stress is always greater than that of radial stress, and maximum value of both the stresses are at inner surface of the cylinder.

After autofrettage, it is inferred that the material behaves as elastic-perfectly plastic (Fig. 7). Taking into consideration the Tresca yield criterion, following relations are derived for radial (σ_r) and hoop stress (σ_θ) components for the autofrettaged cylindrical part [46]:

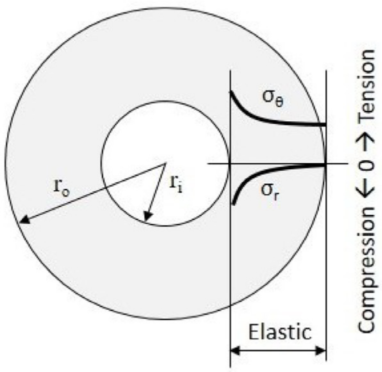
$$\begin{aligned}\sigma_r &= -\sigma_y \ln\frac{a}{r} - \frac{\sigma_y}{2r_o^2}\left(r_o^2 - a^2\right) \\ \sigma_\theta &= \sigma_y\left(1 - \ln\frac{a}{r}\right) - \frac{\sigma_y}{2}\left(1 - \frac{a^2}{r_o^2}\right)\end{aligned} \tag{4}$$



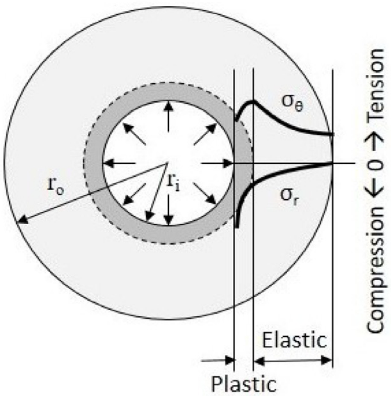
(a) Hoop stress before and after autofrettage



(b) Radial stress before and after autofrettage



(c) Before autofrettage [47]



(d) After autofrettage [47]

Fig. 6. Stress distribution in a cylindrical gun tube before and after autofrettage.

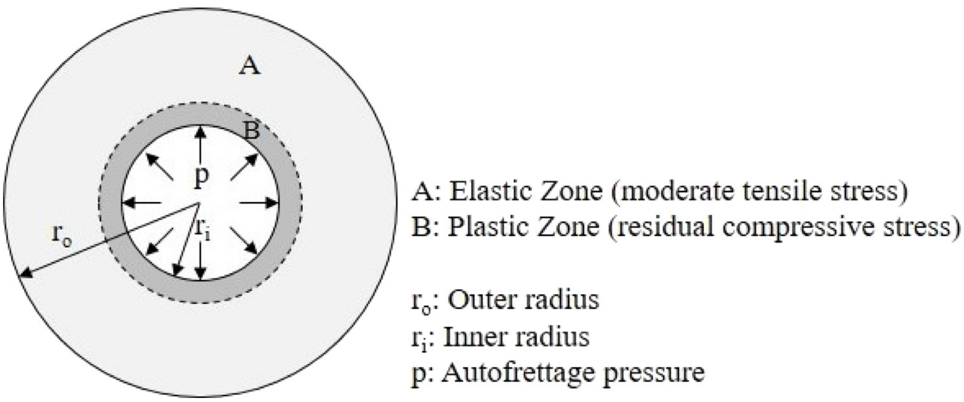


Fig. 7. Creation of elastic–plastic region after autofrettage.

2.1.2. Benefits of autofrettage

- Improvement in lifespan - By uniformly distributing the stresses along the radius, autoftrettage increases the overall number of firing cycles as well as the value of maximum pressure holding capacity.
- Economical - As far as the engineering effects are concerned, in many instances the autofrettaged parts are cost-effective in comparison to the higher cost material with similar strength.
- Negate the effect of poor machining of inner surface - Autofrettage reduces the machining defects by improving the surface finish of inner bore which is otherwise costly and in some cases experimentally prohibitive.

- Elimination of the adverse influence of unavoidable cross-section features - Features like cross holes and other geometric irregularities cause unwanted stress concentration which may be eliminated by using autofrettage process.

3. Gun barrel health monitoring techniques

Gun barrel life can be categorized as — wear life and fatigue life. It has been observed over several years of operations that the fatigue failure is hazardous and can put the lives of gun operators in danger, whereas the barrel wear just reduces the firing accuracy without being fatal to the operators. Hence, the gun designer opts for the barrel in which fatigue life exceeds its wear life. Wear life can be approximated by the total number of rounds fired till denunciation of the barrel. For a large caliber gun, thousands of rounds can be fired before discarding the service of barrel. Therefore, fatigue of gun barrel is low cycle fatigue (LCF).

Thereupon, methods for predicting the gun barrel wear life are basically derived form its wear mechanism. Available methods can be segregated into following approaches and techniques:

3.1. Wear estimation using empirical approaches

Rauf Imam [47] proposed the following mathematical equations for the estimation of erosion with respect to the muzzle velocity:

$$W_2 = W_1 \frac{\Delta_2}{\Delta_1} \left(\frac{P_2}{P_1}\right)^{1/2} \frac{L_2/V_2}{L_1/V_1} \left(\frac{V_2}{V_1}\right)^3 (\mathrm{PF})(\mathrm{CF}) \tag{5}$$

$$W_2 = W_1 \frac{\Delta_2}{\Delta_1} \left(\frac{P_2}{P_1}\right)^{1/2} \frac{L_2/V_2}{L_1/V_1} \left(\frac{\mathrm{e}^{2V_2}}{\mathrm{e}^{2V_1}}\right) (\mathrm{PF})(\mathrm{CF}) \tag{6}$$

where, the subscript 1 refers to the standard cannon (155 mm Howitzer M185) and the subscript 2 refers to the unknown cannon.

The model discussed above does not consider one important factor which is muzzle velocity variation corresponding to the cannon diameter. So, Chung and Oh [48] modified this equation to give:

$$w_2 = w_1 K \frac{V_2^{cV_2}}{V_1^{cV_1}} \tag{7}$$

$$\frac{w_2/w_1}{K} = \frac{V_2^{cV_2}}{V_1^{cV_1}} \tag{8}$$

$$K = \frac{\Delta_2}{\Delta_1} \sqrt{\frac{P_2}{P_1} \frac{L_2/V_2}{L_1/V_1}} (\mathrm{PF})(\mathrm{CF}) \tag{9}$$

where, c is an empirical constant that is specific to cannon tube size (e.g. $c = 0.6$ for 155 mm and 0.7 for 203 mm cannons).

Robert Miner [49] has listed following empirical models to perform initial analytical solution for muzzle velocity:

- Corner's Model

$$v_{mz} = \sqrt{\frac{m_c \lambda (M + \Phi)}{m_p + \frac{m_c}{3}}} \tag{10}$$

- Coppock's Model

$$v_{me} = \sqrt{\frac{\lambda m_c \left(M + Z_b \Phi\right)}{\left(w_1 + \frac{m_c}{3}\right)}} \tag{11}$$

where, w_1 is adjusted projectile mass, and Z_b is the ballistic parameter for form function.

Beer and Hajn [50] performed wear limit assessment based on decrease in muzzle velocity:

$$\Delta c_{0L} = f_w^{-1} \left[v_0(1 - VDL)\right] \tag{12}$$

where, c_{0L} is the limit of change of initial combustion volume, v_0 is muzzle (initial) velocity, and VDL is the velocity decrease limit. This limiting value determines when the barrel should be deactivated from service.

Johnson and Cook [51] studied fracture characteristics of 4340 steel which is generally used as gun barrel material. They introduced a cumulative-damage fracture model which demonstrate the strain to fracture as a function of the strain rate, temperature and pressure.

Strength model for the von Mises tensile flow stress is referred to perform computations to evaluate the fracture model

$$\sigma = (A + B\varepsilon^n)\left[1 + C \ln\left(\dot{\varepsilon}/\dot{\varepsilon}_0\right)\right]\left[1 - \left(\frac{T - T_{\mathrm{r}}}{T_{\mathrm{m}} - T_{\mathrm{r}}}\right)^{\mathrm{m}}\right] \tag{13}$$

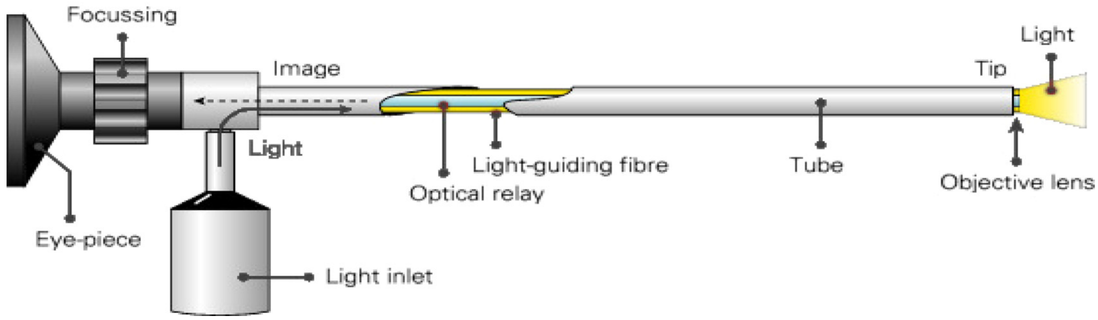


Fig. 8. Side view of a rigid borescope (www.cryptomuseum.com).

The damage parameter is calculated from the expression of equivalent strain to fracture

$$\varepsilon^{f} = \left[D_1 + D_2 e^{D_3\sigma^*}\right]\left[1 + D_4 \ln\left(\dot{\varepsilon}/\dot{\varepsilon}_0\right)\right] \times \left[1 + D_5\left(\frac{T - T_r}{T_m - T_r}\right)\right] \quad (14)$$

Here, the first term says that the strain to fracture decreases as the hydrostatic tension increases. The second term represents the effect of strain rate, and the third represents the effect of temperature.

3.2. Wear measurement techniques in gun barrels

To determine the wear and erosion in large caliber gun barrels, the following equipment have been reported in literature:

- **Borescope** — It is a long, thin cylindrical instrument consisting of lights, lenses, and mirrors which allow any investigator to look closely at the bore surface along its length (Fig. 8). This instrument has a drawback that it cannot be used to measure the depth of erosion [52].
- **Pullover gauge, star gauge and dial bore gauge** — These devices are indicator type gauges which are used to inspect the dimensional variation inside a barrel by measuring the bore diameter at any axial location. The measurement can be done by inserting the gauges either from the breech side (pullover gauge) or from the muzzle side (star gauge and dial bore gauge) of the barrel up to the desired position.
  The dial bore gauges operate on the principle of two diametrically opposed measuring points, one fixed and one moving, plus a spring-loaded centralizing shoe. Whereas, the star gauge examines by placing contact pins vertically (top-to-bottom) and then horizontally (side-to-side) over the entire bore length. In both cases, the diameter is recorded at various axial positions which is then used for the wear or erosion initial estimation.
  Star gauges are mostly used in the gun barrel manufacturing unit for its acceptance after manufacturing, initial proof firing tests and developmental tests. Dial bore gauge can be used at any time after gun firing to check for wear. The consistent recordings after routinely checkup helps in getting information when the barrel wear occurs and accordingly calculating the decisive time to consider replacing the barrel.
- **Optical bore-mapping systems** — Though, above mentioned all the instruments have been used for monitoring of barrel health based on bore diameter, none of them gives complete readings in terms of both quality and quantity. For better visualization of the bore's condition, bore-mapping systems have been developed [52]. These are capable of making optical (or laser) measurements of entire bore, then display the bore condition quantitatively using advanced imaging techniques (Fig. 9). These techniques 'unfold' the cylindrical shape of the barrel into a plane structure which makes the observation easier to comprehend.
- **Wear estimation using ultrasonic waves** — Asymmetric damage inside the barrels can be detected using ultrasonic waves. Wang and Jin [53] used L(0,2) modes excited at 250 kHz, and showed the axial (z), radial (r) and circumferential (ϕ) displacements. They also mentioned that the torsional mode is not frequently used in barrel inspection as it is challenging to attain T(0,1) mode waveform excitation which requires piezoelectric sheet to be deployed all around the contour of the barrel and to stimulate in the tangential direction, which is not always feasible.
- **Wear estimation using diamond indenter** — This device contains the diamond indenter which is used to measure the wear inside the barrel. The modern indenters are equipped with pneumatic mechanism. The indents can be traced by using the X–Y-stage of the measurement system. The wear depth is calculated by converting the variation in the diagonal of each indent after the test. The method allows for the precise measurement of bore wear in a short period of time. It is successfully used to predict the life expectancy of a rifle barrel.

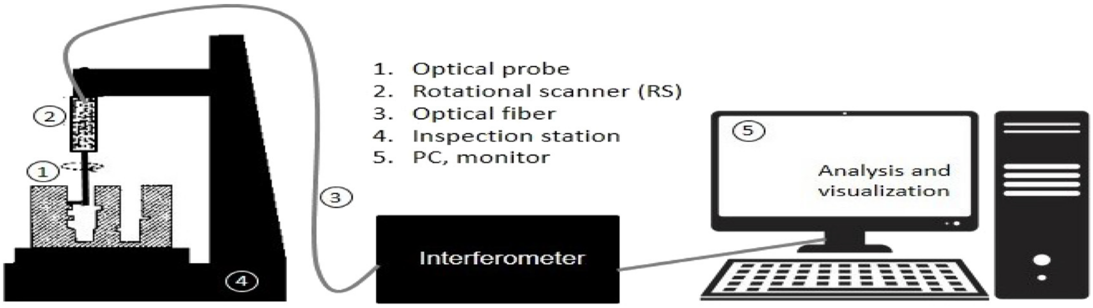


Fig. 9. Optical bore-mapping system.

3.3. Prognostic techniques for predicting RUL

3.3.1. Prognostics and health management

The functional or structural degradation of a system or component presents significant hurdles in assuring acceptable performance levels along with efficient maintenance of such systems or components. Such problems are efficiently resolved when addressed under the realm of so-called condition based maintenance (CBM) and prognostics and health management (PHM) [54–58].

In recent years, predictive maintenance of systems has come to rely heavily upon the prognostics of failure in critical systems/components as failure prediction. It is helpful in providing a sufficient lead-time between detection of a fault (diagnostic step) and occurrence of the system/component failure so that pro-active maintenance actions can be strategized in advance. The Remaining Useful Life (RUL) serves as an efficient indicator of failure prognostics by presenting how long system can function safely/reliably and within the prescribed limits of system functionalities. As such, derivation of RUL depends upon the prediction of system behavior in future.

Prognostic techniques vary according to the assumptions associated with system operation. The prognostic models based on different approaches are discussed below:

- *Probabilistic life usage models based approach* require large sets of historical failure database (failure time or failure rate) of the components to develop life-usage models [59].
- *Data-driven prognostics* processes system data signals mainly using machine learning methods to understand the degradation patterns and features that aid the prediction process [60]; time series forecasting techniques such as auto-regressive models, exponential smoothing techniques, autoregressive moving average (ARMA) models have been exploited extensively [61]. While ARMA and its variants lead to efficient short-term predictions, they prove less reliable for long term predictions mainly due to inherent stochasticity of signals and inefficient uncertainty management.
  Recently, deep neural networks have been extensively exploited as well as developed for efficient prediction of RUL in presence of unknown time varying non-linear stochastic dynamics [58,62]. Various structures have been studied recently for their suitability vis-ó -vis RUL prediction in presence of unknown features/representations often hidden underlaying the acquired sensor measurements such as convolutional neural networks [63,64], Deep recurrent neural networks and their variants [65] have proved particularly efficient in prediction of RUL under variable operational conditions. The efficiency of long term RUL predictions is significantly dependent upon the diversity and richness of the training set and thus remains limited in face of variable degradation trends, novel failure modes etc. [58,66].
- *Model Based Prognostics* typically uses mathematical behavioral models of systems to assess state of health and damage progression. These mathematical models used are usually known as degradation models (DMs) that are typically derived from the first principles of physics. Some examples include fatigue models for assessing propagation of cracks in structural components [67], electrolytic overstress ageing [68], Arrhenius equation for prediction of resistance drift [69], physics inspired power model [70] or log-linear model for degradation of current drain [71], physics-inspired exponential degradation model for aluminum electrolytic capacitors [72]. The accuracy and feasibility of this approach relies directly on the accuracy of mathematical model used to model the underlying degradation process.
- *Hybrid prognostics* combines the benefits of model-based approach and data driven approaches. This is done by employing approximately correct DMs which are then improved over time as new observations arrive in order to obtain the exact damage behavior. Generally, data driven techniques are employed in the early phase, plausibly offline, to capture and learn the damage progression using machine learning techniques that lead to statistically derived mathematical models that fit the given degradation database. Some notable works include: non-linear least square regression [68], relevance vector machine regression [73], DM approximated by a linear part and logarithmic/exponential part [74], residual based statistical DM [75], end of life (EOL) in lithium-ion batteries [76], battery health management [73], estimation–prediction of crack growth [77], fuel cell prognostics [75], prognostics of pneumatic valves [78], mechatronic systems [79] and system level prognostics [80].

3.3.2. Prognostic techniques for predicting wear life of gun barrel

Prognostic techniques refer to the various practices focused on predicting the time at which the ammunition system will no longer perform its expected function. In other words, it denotes the failure beyond which the gun barrel can no longer be used for firing activities. The predicted time then becomes the remaining useful life (RUL). Prognostics of a gun barrel is done by assessing the extent of degradation of the barrel from its expected normal operating conditions. For effective life prediction, prerequistes are — having clear knowledge of the failure mechanism which cause degradation, the analysis of failure modes, detection of early signs of wear, and fault conditions. Thus, focus should be on the initial information on the possible failures like wear rate (erosion or corrosion).

In this section, we have discussed diverse methods used by researchers targeting the information regarding wear rate based upon the heat, dimension, and strain condition of the barrel along with the muzzle velocity of the projectile. These methods for predicting life are related to the wear mechanisms.

- **Heat based method**
  Bin Wu et al. [81] have categorized the gun steel sub-surface into three layers based on the after-effects of thermal loading. The outermost layer, being farthest from the surface, is unaffected by the thermal exposure. Whereas, the innermost layer gets easily affected by the gases released due to the combustion of chemical propellants. Hence, this zone is known as chemically-affected zone (CAZ). The CAZ surface is weak and brittle due to the formation of micro-cracks. These cracks partially or completely detach during the subsequent firing which in turns lead to the formation of new layer of CAZ. Lastly, the intermediate layer, between the inner and outer layers, is thermal affected layer, hence known as heat-affected zone (HAZ). This layer becomes harder and more brittle with each round fired. Based upon the uncoated steel bore gun wear theory, Lawton et al. [82,83] have mentioned that the wear per round of firing depends on the CAZ thickness. In this study, they have worked on a 155 mm AS90 gun with and without wear reducing additive. It is concluded that the addition of additive increases the barrel life (approximately 10 times) by reducing the maximum temperature. In addition, Chung et al. [84] have also derived the mathematical relation of the wear rate as a function of heat transfer into the surface of 40 mm gun tubes:

  $$w(Q) = ae^{bQ} \tag{15}$$

  where, a & b are constants and $Q\,(\mathrm{J/mm^2})$ is the heat input.
  The above derived equation is applicable for the intermediate caliber guns (40–105 mm). As per them, this erosion equation produces accurate cannon tube erosion rates.
- **Dimension based method**
  In large caliber rifled gun, after a certain number of rounds have been fired, both the chamber length and the bore diameter increase due to the bullet–barrel friction and the engraving process, which ultimately reduces the muzzle velocity. One of the methods for predicting the remaining life is based on the increment in chamber dimensions i.e. length and diameter. When the calculated increase in diameter and length reaches the critical value, the gun barrel is excluded from service. Bin Wu et al. [81] have compared the empirical equations of the critical rounds fired with respect to the increase in chamber length and increase in the bore diameter:

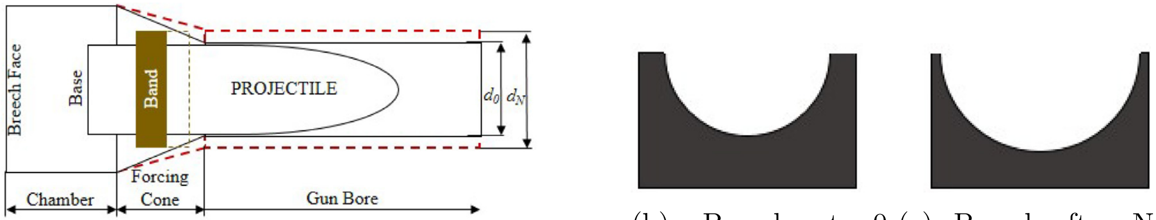
  $$R = f\left(\Delta l_i\right) \quad \text{and} \quad R = f\left(\Delta d_i\right) \tag{16}$$

  where, Δl_i and Δd_i are increase in chamber length and bore diameter respectively, induced from the *ith* round.
  They observed that the method based on the chamber length measurement is not feasible, whereas, the method based on the relation between rounds fired and increase in bore diameter is reasonable to predict the critical number of rounds. The method is restricted to normal wear of uncoated steel barrel. Neglecting the change in material property is one of the limitations of this method. Another limitation arises due to the inability to correctly measure the bore diameter of a gun barrel with precision.
- **Velocity based method**
  For a large caliber rifled gun, the muzzle velocity declines gradually as the wear develops. Consequently, Imam [47] anticipated that the muzzle velocity is the most important parameter involved in the barrel wear. Based upon this hypothesis, mathematical equations explaining the relationship between wear rate and muzzle velocity have been established. These relations are given in Eqs. (5) and (6).
  Additionally, LaVigna et al. [85] suggested certain equations to co-relate the muzzle velocity with the rounds fired:

  $$R = f\left(\Delta v_i\right) \tag{17}$$

  where, Δv_i is decrease in muzzle velocity induced from the *ith* round.
  However, this empirical equation holds a major drawback of not predicting the efficient remaining useful life solely based on the muzzle velocity [81]. It is due to the fact that the wear inside the barrel is not uniform along its length [86], and accordingly it might affect the projectile speed, also the muzzle velocity might also decrease because of several other reasons as well.
- **Strain based method**
  The exterior strain of a gun barrel decreases with the growth of damage caused by rounds fired. Bin Wu et al. [81] proposed a relation between the rounds fired and the decrease in exterior strain of barrel:

  $$R = f\left(\Delta \varepsilon_i\right) \tag{18}$$



(a) Expansion of bore diameter at N rounds

(b) Barrel at 0 round

(c) Barrel after N rounds

Fig. 10. Schematic diagram of barrel failure mechanism due to the projectile's rotating band, (considering barrel is diacarded after 'N' rounds).

where, $\Delta\varepsilon_i$ is the strain difference between *ith* round and *(i + 1)th* rounds, and indicates the extent of damage to barrel by firing *(i + 1)th* round.

They presumed that the gun barrel has to be discarded after firing N rounds. Thus, when the exterior strain decreases from ε_{max} (ε_1) of the first round to ε_{min} (ε_N) of the last round, the gun barrel's useful life ends.

3.4. Other noteworthy techniques

Apart from various methods discussed in previous section, there are few other techniques available in literature which addresses the RUL by considering the effect of fatigue, temperature gradient, and thermo-chemical erosion. These techniques are discussed individually in the following section.

3.4.1. Effect of fatigue on RUL of gun barrels

Multiple rounds of firing causes cyclic loading on the material which result into crack propagation followed by fatigue failure of the barrels. Initial crack size is a dominant factor for life degradation. The probabilistic model demonstrate that the large cracks reduces the RUL which may be mathematically be modeled with exponential or Weibull distribution [87].

Crack propagation is influenced by residual stresses developed due to the autofrettage. Its effect is studied by Perl and Saley [88,89] for internal and external cracks [90,91]. Based on stress intensity factor (SIF) values it was concluded that the autofrettage improves the fatigue life for internal cracks, whereas it causes adverse effect on external cracks. Additionally, numerical simulations show that the autofrettage resist the propagation of cracks due to the residual compressive stress and hence these barrels have high RUL than the non-autofrettaged barrels [92].

Along with the deteriorating effects of fatigue, the interaction between bullet and barrel also plays a crucial role on RUL of barrels. Bullet–barrel interaction is affected by the bullet design which usually comprises of a driving band, casing, core, and lining. Andrews [93] worked on 155 mm gun barrel and stated that the interference between the driving band and gun barrel lead to cracking and wear of the barrel. The similar outcomes for the bullet structure is presented by Zelenko et al. [94] for the sniper cartridge. It is also demonstrated that the wear of a barrel varies depending upon the bullet design. A schematic diagram in Figs. 10(b) and 10(c) shows that the interference of bullet driving band with the barrel increases the bore diameter.

In the course of a firing cycle, the bullet (projectile) accelerates in addition to in-axis rotation. The acceleration and rotation of bullet increases the wear of the bore surface with each cycle, causing a reduction in the muzzle velocity. This affects the projectile's trajectory, shooting intensity, and accuracy of the exterior ballistic performance. The ballistic performance of a 12.7 mm machine gun barrel is simulated by Shen et al. [95]. It is shown that with the increase in bore diameter, the bullet's initial disturbance increases. This disturbance causes vibration at the muzzle which affects the bullet's forward momentum and hence decreasing the ballistic performance [96,97]. A few other noteworthy works which show the significance of fatigue analysis and crack propagation on the gun barrel life are listed below in Table 2.

3.4.2. Effect of heat flux and temperature rise on RUL of gun barrels

After a shot is fired from gun, the heat from burning propellant gases is transferred to the bore surface through a thermal convection phenomenon. If there is sufficient time between each shot fired, the hot barrel is cooled down by convection and radiation to the outer surface. As the firing frequency is increased, i.e., the barrel temperature rises sharply and reach the cook-off temperature. This may result in unfavorable effects like melting of bore surface material, premature self-ignition of charges, wear due to erosion, cracks, etc. So, as a precaution to reduce the cook-off temperature, cooling methods are employed. These methods are classified into passive (chrome plating and wear-reducing additives) and active (forced liquid cooling).

Apart from the aforementioned heat-based methods (in Section 3.3.2), which are empirical, there are few developments that have been made for gun barrel RUL prediction. It includes modeling and simulation of heat flux estimation using inverse methods. An inverse method with FE analysis is presented by Chen et al. [105] for estimating time-varying unknown surface heat flux. It is found that the heat flux can melt/erode the bore surface material. Hence, it may be concluded that thermal factors are the most critical contributors to barrel erosion. Another inverse algorithm-based conjugate gradient method is used by Lee et al. [106] to determine the time-dependent heat flux and thermal stress distributions. A 3-D inverse heat transfer analysis model is developed by

Table 2
Remaining useful life estimation of gun barrel based on wear and crack propagation.

Objective	Methodology — principle	Study output	Observations/Remark
Underwood et al. [98–100] performed a full-scale fatigue life analysis to show the effect of applied pressure, residual stress, and initial crack size on the barrel life for a 120 mm tank cannon	Used pulse-echo ultrasonic non-destructive based inspection (NDI) technique to monitor crack growth	(a) Initial crack size has a vital effect on fatigue life, (b) crack from thermal damage is crucial next to erosion for barrel fatigue life	Crack growth rate investigation is not feasible for minor cracks (<2 mm)
Banks-Sills and Eliasi [101] conducted fatigue life analysis of a steel cannon barrel	Performed FE analyses and statistical Monte Carlo simulation	Deterministic value of the fatigue life is found to be 25% lower than that of the statistical analysis	For 10% increment in the initial crack length, there is a 4.3% reduction in the fatigue lifetime
Precision wear rate measurement of high friction and high pressurized gun barrel (155 mm XM199) was done by Chung et al. [102]	The setup includes an indentation apparatus and an optical measuring system, along with the SEM to verify the accuracy of wear measurement	The predicted amount of wear as a function of the number of rounds agrees with the result from a bore gauge and the empirical solution	The diamond indent after the firing has the same shape but smaller size, so, the change in size (decrease in the short diagonal of the indent) is converted to amount of wear
2-D modeling of short crack propagation kinetics during firings of a 120 mm gun barrel was studied by Petitpas and Campion [103]	(a) Introduced cracks of increasing length in the model to calculate the stress intensity factor, (b) Analyzed the effect of autofrettage on crack propagation	(a) Small crack propagation is accelerated by thermo-mechanical stresses, (b) Kinetics of large cracks (over 4 mm) propagation are governed by the pressure effect	Autofrettage to a depth of the order of 20 mm increases the number of critical firings by a factor of 10
R Mahdavinejad [104] performed stress analysis on crack tip is carried out using ANSYS software for 155 mm cannon barrel	The fatigue with several (one, two, three, four, and twenty-five) cracks is analyzed in the barrel according to the critical explosion pressure	The stress intensity on the tip of the crack is a function of its length and increases with the number of these cracks	When the number of the cracks is more than two then, the interaction between the cracks causes the improvement of the cannon's barrel life

Noh et al. [107,108] for heat flux estimation of a multi-layered tube having varying cross-sections. It is ascertained that the heat flux intensity increases with the increasing number of rounds fired, and it tends to decrease with respect to position towards the muzzle. For the outer layer of the barrel, it is recognized that an increase in the number of rounds causes an increase in temperature.

Computing the barrel temperature history with accuracy is essential for the thermal management of the gun barrel. For temperature prediction, there are various interior ballistic codes developed and revised by researchers. These codes consider conduction, convection, and radiation-based heat transfer equations. XBR2D-V29 heat transfer code and one-dimensional radial heat conduction code are used by Conroy et al. [109,110] for 120-mm cannon and 155-mm gun barrel, respectively. These codes work very well for the initial temperature rise prediction in the barrel. Some of the other remarkable works in regard to the gun barrel temperature estimation are listed in Table 3.

3.4.3. Effect of coatings and thermal erosion of RUL of gun barrels

Gun barrel erosion is referred to as thermochemical erosion. It is associated with the combined effect of both thermal erosion (melting of bore surface) and chemical erosion (removal of surface material). The surface erosion rate mainly depends on the heat-affected zone (HAZ), and it tends to accelerate depending on the chemically affected zone (CAZ). As discussed in Section 2.1, one of the practical methods to avoid erosion is by using the standard ERAMs. The most commonly used additive material to protect the bore surface against erosion wear is chromium. Chromium is applied as a galvanic layer of around 0.1 mm. The chrome layer also provides high hardness and corrosion resistance to the bore surface. However, during an operation where numerous rounds are fired continuously, the chromium layer as well as the inner steel surface may heat intensively. If the risen temperature exceeds a limit it might change the gun metal's phase. This phenomenon is accelerated in the presence of inherent cracks in chrome. It leads the hot gases to the gun material surface beneath the chrome layer where they react and pits are formed. The hottest location is the interface between the chromium layer and the gun steel at the bottom of the crack, which makes it the most reactive as well. Fig. 11 describes a magnified schematic diagram of a microscopic image of a crack propagated through the chrome layer to the gun steel layer and the occurrence of the erosion pit.

Various internal ballistics codes have also been developed for the erosion study of the gun barrels. The first known gun barrel thermochemical erosion modeling code is presented by Sopok et al. [120] using the 155 mm M203 Unicannon system. The other codes include 1-D NOVA codes for interior ballistic analysis, BLAKE codes for gas thermochemical equilibrium analysis, TDK/MABL codes for boundary layer addition analysis, TDK/ODE codes for gas-wall thermochemical equilibrium analysis, and MACE codes for ablation, erosion, and temperature profile analysis. Using these five module analyses temperature and heat flux profiles (time and axial position) is plotted. It is noticed that at the axial position having maximum heat, the uncracked gun steel eroded much more than the uncracked chromium material by single-shot. A few other related works is discussed in Table 4.

Table 3
Gun barrel RUL prediction based on temperature rise and cook-off failure.

Objective	Methodology — principle	Study output	Observations/Remark
Yang et al. [111] determined barrel life based on heat flux and thermal stresses in a multilayered gun barrel (steel cylinder with chrome coating) by considering transient heat transfer and interlayer thermal contact resistance	Applied a hybrid numerical method of the Laplace transformation with the finite difference, and numerically calculated the transient temperature distributions and thermal stresses	Variation of hoop stress, radial stress, and axial stress in the steel region is found to be more radical than that in the chrome region during the heating periods	The maximum radial stress increases as a function of time during the heating periods, and it disappears at the inner and outer surfaces of the gun barrel
Mishra et al. [112,113] developed an IB code and employed FEA method to model gun barrel temperature variation over time for its wear calculation	Performed 1D transient thermal analysis with the FEA package ANSYS for single and series of cycles on 155 mm, 52 caliber gun barrel, and validated experimentally	It accurately simulates gun barrel temperature history, hence, better wear calculations and predictions can be made	(a) Erosion of the gun barrel is dependent on the maximum bore surface temperature, (b) Midwall and external cooling technique can eliminate the possibility of cook-off
Yuhas et al. [114] developed an ultrasonic-based sensor in order to measure internal bore temperature at critical areas on large caliber gun barrels	Ultrasonic sensor was mounted on the exterior surface of an MK45 MOD 4 gun which is made up of fine-grained steel capable of propagating high-frequency ultrasound (>30 MHz)	The first echo arises from grooves, whereas the second echo is from lands having a separation of approximately 440 nanoseconds. The temperature localization relies on these echo doublet	The ultrasonic technique used here has adequate temporal response and sensitivity and hence can be used where cook-off (auto-ignition) is of concern
Akcay and Yükselen [115] prepared a 1D axially symmetrical unsteady heat transfer model for the heat transfer calculation of 7.62 mm M60 Machine gun barrel	Separately derived the temperature distribution for internal points and surface boundary points by means of internal ballistic theory, and solved it numerically by FDM	The calculated theoretical number of firing rounds for cook-off (130 rounds) is indeed very close to the experimental result (120 rounds)	The proposed model can also be used for similar small and large caliber gun barrels, and by following this technique the cook-off condition can also be predicted
Şentürk et al. [116] used a thermo-mechanically coupled theory for experimental, numerical, and analytical ballistics solution of a 7.62 mm gun barrel	Used ANSYS for temperature distribution in radial and axial directions, and calculated pressure distribution, projectile velocity snd position, and temperature of burnt gases along the barrel	The maximum von Mises stresses for finite element (ANSYS) and analytical solutions are found to be close to each other for both cases of a single shot and multiple shots	To design a barrel for strength an insight to single shot stress state of the barrel is sufficient, whereas to design for safety against cook-off it needs a number of successive shots
Değirmenci et al. [117,118] developed a numerical and thermo-mechanical FE model of a 7.62 mm caliber gun barrel in Abaqus to study thermal effects and stresses on barrel behavior	Determined the convection heat transfer coefficient and combustion characteristics of propellants with various grain sizes by shooting tests, and analyzed the inner and outer wall temperature	Thermal stresses are most prominent on the inner surface at the first shooting, but as the successive shots are fired thermal stresses on the inner wall decreased while that on the outer wall increased	With increase in initial temperature of the solid propellant or decrease in the grain size, the inner and outer wall temperatures, internal pressure and bullet velocity increases
Ding et al. [119] formulated parametric geometric modeling of the worn barrel with novel FE meshing strategy, and accordingly studied the worn barrel-projectile interaction analysis	Developed the modeling method using Python code & ABAQUS/CAE software, computed the plastic deformation of rotating band and the performance of interior ballistics	The method adequately predicted the global responses (muzzle velocity & maximum chamber pressure) and local effects (localized thermal distribution & plastic deformation of the band)	(a) The maximum pressure is more prone to the wear of gun bore than the muzzle velocity, (b) In worn barrel, the friction resistance of the rotating band decreases which degrades the IB performance

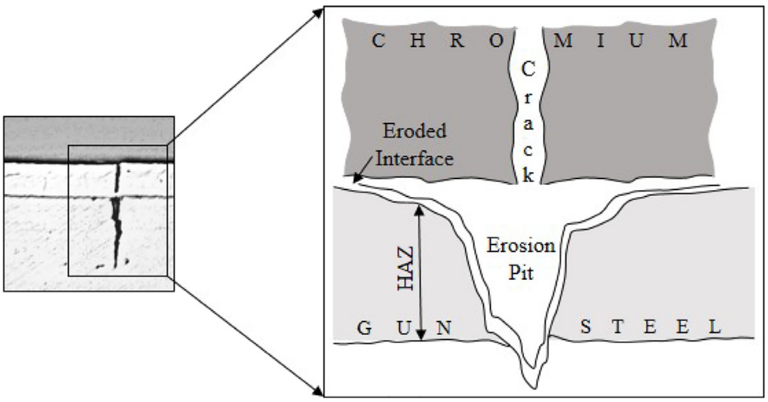


Fig. 11. Magnified image of a microscopic crack due to thermochemical erosion.

Table 4
Remaining useful life improvement of Gun barrel by use of coatings.

Researcher with objective	Methodology — principle	Study output	Observations/Remark
Cote and Rickard [121] studied the erosion initiation of steel under the protective chromium coating in 120 mm (M256) and 155 mm (M199 & XM297) gun barrels	Examined the barrel specimens by optical microscopy, laser scanning confocal microscopy (LSCM), and through the electron microprobe analyses	Chemical charge is the originator to erosion damage into the steel, and with higher flame temperature, corrosion increment of chromium coating occurs	Required coating features: (a) chemically inert, (b) high thermal shock resistance, (c) resistance to coating cracking from sliding wear
Sopok [122] performed an optimization study of the gun bore protection materials using a thermal–chemical vented combustor erosion model	Used erosion prediction algorithms such as CCET thermochemistry cannon, XNOVAKTC interior ballistics, MABL, and MACE	Erosive degradation thresholds are governed by oxidizing, carburizing, or intermediate-reducing solid propellant combustion environment	Cannon bore protection materials include pure chromium, high & low contraction chromium, tantalum, molybdenum, rhenium, and niobium
Conroy et al. [123] studied non-equilibrium (finite-rate) and equilibrium (infinite-rate) chemical kinetics of erosion for chromium plated M256 120 mm tank canon	NSRG codes are used for non-equilibrium chemical kinetics	Down-bore erosion in the equilibrium is more than the non-equilibrium	Under similar circumstances tantalum may erode more than chromium due to its physical properties
Underwood et al. [124] adapted concepts of Evans & Hutchinson [125] for FE study of slip-zone coating failure for chromium and silicon carbide bore surface of 120 mm cannon	Thermo-mechanical modeling is extended to include time-varying gas temperature and convection coefficient data as inputs, also extended to constant heat input conditions	Higher interface temperature causes more softening of the thin chromium and lower shear strength at the interface which results in more severe thermal damage	Three measures of thermal damage are described: peak near-bore temperatures, the temperature difference between the heated surface and 0.1 mm below the surface, and coating segment shear stress
Sopok et al. [126,127] developed erosion models based on thermal, chemical, and mechanical gun bore erosion theories and mechanisms	The devised models, predictions, and mitigation efforts are used for estimating the erosion life for various coating types	Erosion life of low contraction chromium (LC-Cr) plated guns exceeds that of high contraction chromium (HC-Cr) by a factor of more than 2	Emphasized on location and mechanisms of the erosion process
de Rosset and Montgomery [128] examined the degree of wear and erosion by multiple firing tests of a small caliber gun barrel made of a cobalt-base alloy	The bore diameters are measured with a laser system i.e. bore erosion measurement and inspection system (BEMIS)	Qualitatively (without modeling) explained that the cobalt-base alloy is an excellent gun liner material	Elimination of chemical and thermal effects produces unusual wear pattern
Wang et al. [129] characterized the damage features of a machine gun barrel to explore its failure mechanism	Failure of the gun barrel is correlated with the peeling and wearing of the Cr layer on the bore surface from gun tail to muzzle	The damage rate in both the tail and the muzzle is higher than that in the middle of the barrel	3D intelligent hyperfield microscopy (3DIHM) is introduced for the first time into the study of gun barrel damage
Li et al. [130] established an isothermal erosion model for a machine gun barrel and used a numerical simulation method to study the bore erosion under typical shooting conditions	Barrel material erosion process is divided into three steps- (a) slow erosion step, (b) thermal–chemical erosion step, and (c) melting erosion step	It is confirmed that the thermal–chemical erosion is predominant failure mechanism at the start of rifling, also the erosion zone expands with the increase in firing frequency	The impact of melting degradation can be overlooked since thermal–chemical erosion occurs primarily in the starting region of barrel rifling
Luo [131] used plasma quenching technology on the inner surface material of the gun barrel to improve resistance against wear and corrosion	The inner wall is rapidly austenitized and then rapidly cooled to form a fine martensite structure	The surface hardness is increased (from 320HV to the highest 750HV) and surface abrasion resistance is enhanced (around 11 times)	After the plasma quenching, the wear mechanism changes from sticky wear to abrasive wear

4. Discussion and conclusion

The paper at length discusses various causes of gun barrels' failure which mainly occur due to large mechanical stresses (radial, hoop stresses), and fatigue occurs at high pressure during firing. Presently, Autofrettage is the state-of-the-art technique that reduces the radial stresses at the inner layers of the barrel. The other reasons for degradation of barrel failure include thermal, and chemical reasons such as crack propagation, erosion, wear growth, etc. Various mathematical relations have been formulated by researchers to estimate the degradation rate and hence predict the life of the barrel. The formulas determine the degradation profile by estimating the wear rate and erosion in the barrels. The empirical relations derived by the researchers to calculate the wear and erosion have their own assumptions and limitations which provide the wear information and the barrel degradation, hence predicting the useful life of the barrels. It is also discussed that in order to reduce erosion and wear, additives and coating are the best solutions respectively. However, their durability at high temperature, pressure, and cyclic loading e.g. at high-pressure conditions of the barrel environment is not verified.

Furthermore, we have discussed various techniques for diagnosing the gun barrels such as wear estimation using Boroscope, star gauge, optical technique, and ultrasonic methods. The measurement carried out by these instruments can be used to predict the wear and erosion rates for different ranges of small and large size cannons. The methods include (1) Continuous heat monitoring method which estimates the wear life as a function of heat release due to friction and the gun barrel (2) Dimension based method, in which we measure the change in dimension of bore diameter and the chamber length, (3) Velocity based method in which the muzzle velocity with respect to each shot and the remaining life is predicted as a function of change in velocity, (4) strain-based methods which measure the strain based upon round fired and estimates the life as a function of change in strain. The measurement data from these instruments may further be used to fit in data prediction models such as the Probabilistic model, data-driven model, prognostics model, hybrid models, machine learning, etc.

Following points can be used for summarizing our review of various kinds of research in the field of gun barrel health monitoring and prognostics:

- Addition of additives increases the barrel life, the additives used by the researchers TiO_2 are considered to be the best due to their ability of not producing the residues in the barrel.
- Decrease in muzzle velocity is one of the major observable effects caused by barrel wear. Thus, muzzle velocity is among the best parameters to estimate wear calculation.
- Diamond indenter and optical bore-mapping systems are the best manually operated apparatus available for getting quantitative and qualitative information on gun barrel wear. The ultrasonic waves are the non-destructive state-of-the-art technique in the field of gun barrel wear calculation.
- Strain measurement is considered as the best technique for barrel life prediction approach based upon the wear.

5. Future scope

In the available literature, different diagnosis techniques and causes of degradation of gun barrels have been independently discussed. However, till date, no research discuss their coupled effects as a function of time. Moreover, the research on microscopic study of the Autofrettage gun barrels is not discussed. Based on the available state-of-the-art techniques, a few potential futuristic aspect are discussed as follows:

- Study of microstructures of the cracks developed by the combined effect of thermochemical erosion as well as by fatigue,
- Study of cracks in autofrettaged and non-autofrettaged gun barrels apart from the effect of residual stress,
- Active health monitoring of the barrels is a challenge due to their sustainability of sensors at high temperature and various weather conditions,
- Implementation of Machine learning or Deep learning concepts to predict to estimate the RUL of barrels.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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