Determination of Wear Rate Equation and Estimation of Residual Life of 155mm Autofrettaged Gun Barrel

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ABSTRACT

Wear of steel at high temperature is a complex phenomenon. Quantification of wear per event is an important aspect in assessing life of a component. Necessity of economics and light weighted components compels to study the system under common parameters and extrapolate the results. Temperatures/pressures inside a gun are impossible to be measured by direct methods. Mathematical modeling and comparison of results with end effect measurable parameters is only way to predict it's accuracy.

There is no one such quantitative demonstration which can predict accurate wear rate. Gun wear is unique to gun system and no one theory fits into predictions of gun wear. Gun wear is unique phenomena wrt any particular gun system and needs to be studied independently. Numerous studies have been carried to study steel wear below 600°C. Wear studies at higher temperature i.e. above 600°C is not enough to describe correct wear phenomena.

Keywords: Steel Wear, Steel wear at high temperature, High Temperature Wear Theories, Simulation, Gun Barrel Wear,

1. INTRODUCTION

Wear of steel at high temperature is a complex phenomenon. Quantification of wear per event is an important aspect in assessing life of a component. Necessity of economics and light weighted components compels to study the system under common parameters and extrapolate the results. Temperatures/pressures inside a gun are impossible to be measured by direct methods. Mathematical modeling and comparison of results with end effect measurable parameters is only way to predict it's accuracy.

Wear of steel at high temperature is a complex phenomenon. Quantification of wear per event is an important aspect in assessing life of a component. Necessity of economics and light weighted components compels to study the system under common parameters and extrapolate the results. Temperatures/pressures inside a gun are impossible to be measured by direct methods. Mathematical modeling and comparison of results with end effect measurable parameters is only way to predict it's accuracy.

Manufacture of gun tube is an expensive proposal. Requirement of safety is prime importance and thereby generally it is overdesigned. It costs dearly thereby restricts total available quantum. A tube designed for adequate strength will enhance overall availability. Presently existing tube life can be enhanced to reduce burden on manufacturing agencies/Exchequer. Assessing wear rate of steel is an important study for design engineer for design of optimum gun system.

There is no one such quantitative demonstration which can predict accurate wear rate. Gun wear is unique to gun system and no one theory fits into predictions of gun wear[1,2,3,4] . Gun wear is unique phenomena w.r.t. any particular gun system and needs to be studied independently. Numerous studies have been carried to study steel wear below 600ºC. Wear studies at higher temperature i.e. above 600ºC[1,2,5] is not enough to describe correct wear phenomena.

Gun barrel wear is a complex phenomenon and has been difficult to understand. A unique pattern is observed with each gun system. Early formulas derived by Jones[6] were modified by Shulyer[6] and Kent[7] stated that gun wear is independent of shot mass. However both deferred on relationship of wear with size. Shulyer[6] stated that wear is independent of size and Kent suggested wear is inversely proportional to 2.91th power of bore. Thornhill[8] linked the wear with the heat transfer. Cuthbert and Parry[9] supported Thornhill[8] and stated that wear increases with flame temperature of gasses even when muzzle velocities were kept constant by varying charge masses . No significant wear was noticed below 600ºC . Between 600ºC to 1000ºC, wear increased with moderate rate and after 1000ºC, it increased rapidly. Kanhere[10] related volume removal rate of steel with KE of propellant gases and surface hardness. Criteria of Kanhere is not advocated by majority of authors.

Izak M Synmam[11] simulated gun wear assigning it to be caused by temperature and heat transfer alone as proposed by Thornhill[8]. Lawtan[12] stated that gas leakage through driving band causes excessive temperature rise and leads to high wear rates. He simulated and experimentally verified in close vessel experiments. However no experimental results on actual autofrettaged tube system were given. Peter[13] stated that plastic deformation in gun barrel above 750ºC plays a major role in wear gun in comparison to static or kinematics friction.

J. K. Kim B. D. Choi[14] carried out experimental study to predict approximate life gun 155mm (self propelled) gun. C98 tube was studied and results were extrapolated to approximate the new life. Study was carried out by firing few rounds with each tube and results were extrapolated. Autofrettaged tubes considered were in early stages of life, so no consideration was give to older and used tubes, so statement of Lawtan[12] could not be commented. Xiiaogang Huang[15] studied thermal behavior of 5.56 mm ceramic gun barrels. He stated that maximum peak temperature is achieved within 20% of total travel time and stays for less than 0.2% of time travelled. It is extremely difficult to verify results with desired accuracy.

In a study of barrel life assessment Munger[16] also attributed heat as a major player in barrel projectile interaction. Mechanical wear is insignificant as compared to wear due to heat. Yavon[17] developed a theoretical model to gun barrel wear and result were predicted against laboratory models of ballistic gun under controlled environment with known and verified projectiles. Regression formulas thus derived did not consider actual field conditions and were derived under ideal conditions with tubes in initial stages of life. Gun tube erosion is more rapid and prominent in enlarged guns due to higher leakage of gases in worn out guns[3],[9,12,19,20] and variation in heat transfer rates[19].

Xin[18] and Shang developed FE models for cold formed channels. He validated his models with results of Hans Cock 1998, and the developed virtual test results for range of cold formed channels. He suggested through simulation updating of coefficients in design formula for more reliability. He suggested that simulation is an efficient way of predictions without experimental validation over effective range.

Correct gun barrel wear and predictions of residual life is important information for any defence organization owing to fact of its importance in formulating defense potential indices, procurement plans and defense budgeting. Model is to be developed for each type of gun system as no universal answer is available. Model so developed should be more akin to operating variable of that system. From discussion above it appears that wear rate suggested by Schulyer, Kent and Thornhill may throw some light on wear patterns in autofrettaged tubes operating at very high temperature and pressure.

1.1 METHODOLOGY

Shots were fired and measurement of wear was taken in 155mm tubes. Measurements of gun barrel wear were taken in guns with different life i.e. latest guns, mid life guns and worn out guns.

Result were plotted to ascertain surety levels[21] so R^2 analysis of data was carried out. Different equations were fitted in data series with help of Mathematica 7. R^2 (coefficient of determination)[21] for each equation were determined, selection was based on best fit as it gave satisfactory assurance level.

Mathematica 7 used for solving all equations.

R^2 (Pearson product moment correlation coefficient) is

$$r = \frac{\sum (x-\bar{x})(y-\bar{y})}{\sum (x-\bar{x})^2 \sum (y-\bar{y})^2}$$

Wear rates were also determinded based on barrel wear theories and comparison graphs drawn:-

Schulyer's Criteria[3] for wear is,

$$Wear = Constant \times \frac{C_m^{\,12} m^6}{l^{1.6} d^{16.4}}$$

C is charge mass, m is projetile mass, l is length of projectile and d is diameter of projectile.

Value of constant is unique for each system. Maximum permissible wear taken, so as to avoid mechanical failure, is 51.87 mm [19,24,25].

Kent's Criteria[2],

$$Wear = Constant \times \frac{P_{Max}^{\,1.761} C_m^{1.705}}{d^{2.91}}$$

Value of P_{Max} is calculated as per Internal ballistics relationships[22]

Thornhill's Criteria[1] is

$$Wear = Constant \times d^{0.5}\left\{1 - \frac{T_{CR} - T_i}{T_{\max} - T_i}\right\}$$

where T_{cr} is melting temperature of steel.

Value of T_{max} is calculated as per Internal ballistics relationships[22]

$$\frac{df}{dt} = -\beta p^n$$

$$m(1 + \varepsilon k^2 d^2)\left(\frac{dv_p}{dt}\right) = A(p_s - p_a) - R$$

$$\frac{ds}{dt} = v_p$$

$$V = K + \frac{A(s - s_0 - C(1 - z))}{\rho_{prop}}$$

$$z = (1 - f)(1 + \theta f)$$

$$p(v - \eta) = nRT$$

$$p = \left(p_s + \frac{C}{2A}\frac{d}{dt}[(z + (1 - z)z^k)]v_p + \frac{kCzv_p^2}{d^3}\right)$$

Best fit equation for Measured Wear is;

Wear $= 6.54554 \times 10^{-14}$EFC^4 $- 5.01507 \times 10^{-10}$EFC^3 $+ 1.19058 \times 10^{-06}$EFC^2 $+ 4.90864 \times 10^{-03}$ EFC $+ 7.27686 \times 10^{-01}$

Relationship of Charge mass with EFC, for the given system is

EFC$= -0.397415 + 0.37056 \times -0.080205\, x^2 + 0.00610115\, x^3$

x = Propellant charge weight

When propellant weight and EFC equations are corelated with wear equation the solution gives four roots, one positive, one negative, two imaginery values. Collecting all positive values and plotiing best fit for the same with respect to EFC is given in fiugre 1 below

Plot for estimated wear as per Shulyer, Kent and Thornhill are plottted against measured wear and are given in figure 02.

2. RESULTS AND DISCUSSION

Kents' and Thornhill wear pattern are almost parallel. If maximum wear is taken as equal to measured wear graph, then they are almost overlapping. Schulyer's criteria can not be applied due to very high deviations from measurements.

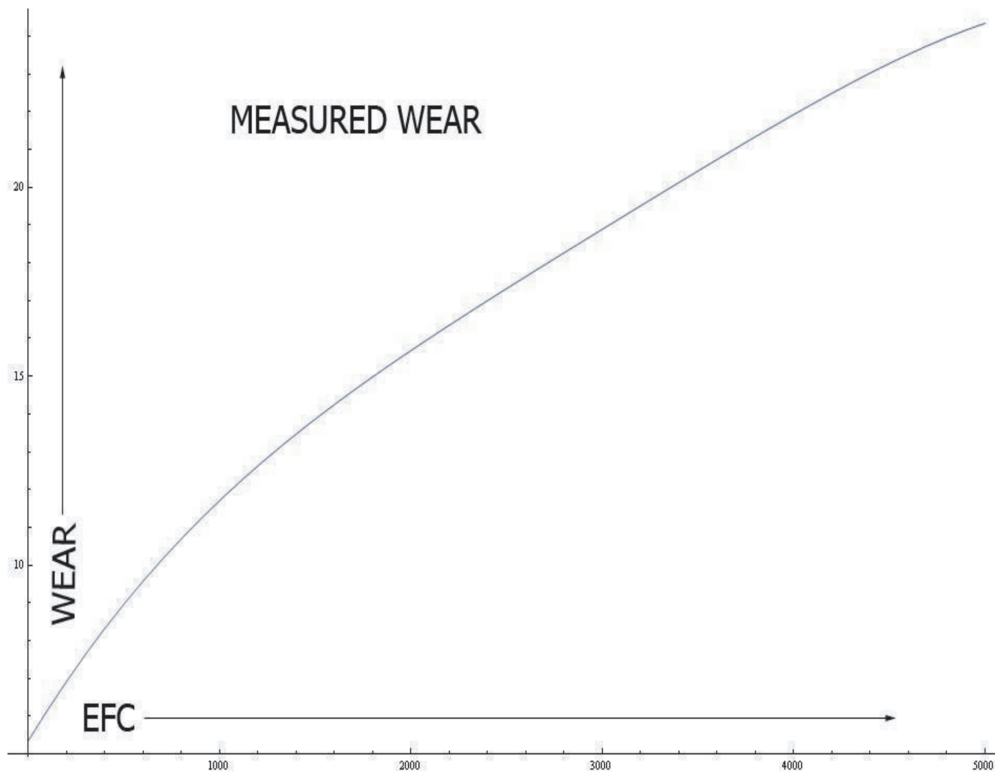

Figure 1 Plot of Best Fit for Measured Wear
Wear = $6.54554\times10^{-14}EFC^4 - 5.01507\times10^{-10}EFC^3 + 1.19058\times10^{-06}EFC^2 + 4.90864\times10^{-03}EFC + 7.27686\times10^{-01}$
R^2 for the above data is = 9.75153×10^{-01}
Wear=5.83073×10^{-3} EFC + 6.16663×10^{-1}, (Linear Relationship)
$R^2 = 9.74851\times10^{-1}$

Thornhiil's criteria is almost a strainght line. It may be due to the fact that maximum rounds fired by this gun system are charge 6 and less then 1.5% are higher charges. Multiplying thornhills's constant by a fixed value gives a overlapping graph to measured wear graph. Thornhill's criteria with this amedned wear rate constant is best solution for this gun system.

Kents' criteria agrees with measured wear pattern for initial stages of progress of wear. It's deviation there after is higher over mesured wear pattern. Multiplying kent's criteria graph data with an additional constant makes it almost parallel to measured wear graph with an offset.

Wear=5.83073×10^{-3} EFC + 6.16663×10^{-1}, R^2 = 97.4851% (Linear Relationship) is best fit equation with respect to EFC for 155mm gun tube with assurance level of 97.48 for the given set of gun tubes.

Simple relationship for Resudual life of each tube; derived for Balance Life in EFC is

$$\frac{Max\ \ Permissible\ \ Wear - Present\ \ Wear - 6.16663\times10^{-1}}{5.83073\times10^{-3}}$$

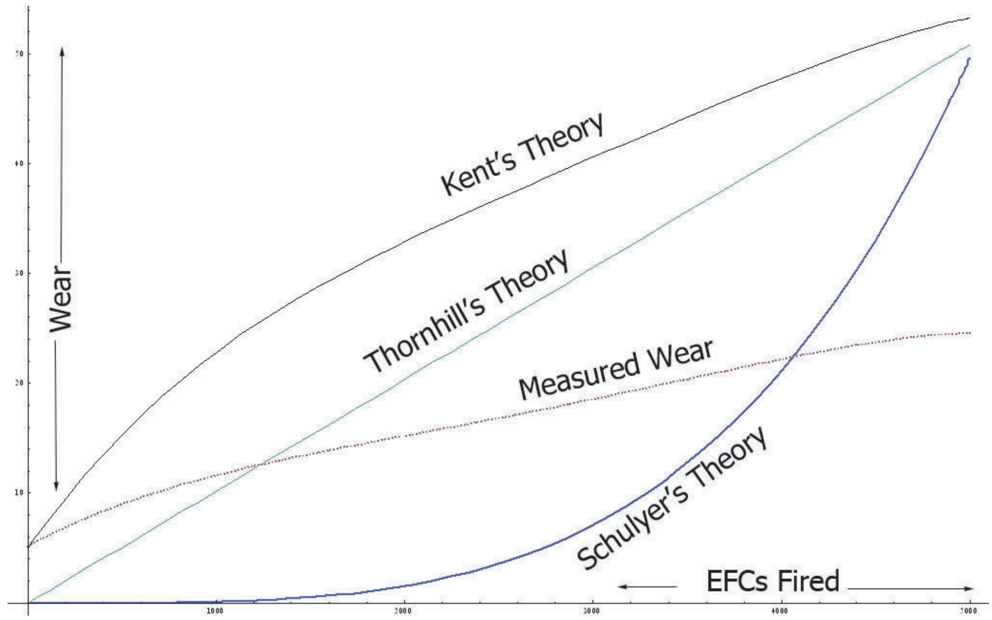

Figure 2 Plot of Theoritical Wear Artes and Experimental Data

Same can be converted into total charge mass to be fired with the help of equations given in paragraph 11 above

Maximum permissible wear is permissible limits of wear acceptable in gun tubes, so as not have caused mechanical failure and loss of effectiveness of projectile. Maximum permissible wear is determined keeping in consideration mechanical strength and loss of muzzle velocity below appreciable limits [22,23,24,25] to retain usefulness of the weapon system.

Balance life in EFCs to be divided in four quarters. Wear and life to be reassessed after each quarter to overcome unpredictability due to unexplained variance. It is recommended for safety of the crew.

No single theory is perfectly applicable to determine wear rate of given gun system which are being operated in respective environment i.e weather, temperature, projectiles, propellant properties, degradation of propellant, driving bands etc. However Kent's and Thornhill's criteria results provide almost similar predictable pattern for wear rate.

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