Damage and fracture of gun barrel under wear-fatigue interaction

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Abstract. Gun, projectile and propellant are three fundamental components of a launching system. Generally, a barrel has to be condemned after a number of rounds have been fired. During the total useful life of gun barrel, it bears severe damage induced from erosion by high pressure and high temperature propellant combustion gas, and wear due to high speed friction between projectile and gun bore. Meanwhile, the gun barrel undergoes a dynamic loading of gas pressure, mechanical stress and thermal stress when firing a round. Thousands of firing cycles lead to gun barrel fatigue. Interaction of wear, including erosion, and fatigue damages the gun barrel and eventually the gun will become inaccurate because of wearing away gun bore materials. However, a gun barrel will fracture in a sudden manner because of fatigue. It is found that microcracks form on the bore surface after only a few rounds have been fired, which lays the foundation for growth and propagation of cracks under fatigue loading. In this paper, laboratory hydraulic fatigue tests were carried out on a tube with pre-machined crack on its inner surface by using an MTS 809. Strain gauges were adhered to the outer surface of the tube to monitor strain during testing process. The hydraulic oil pressure was measured by a pressure sensor. The experimental results show that there are three stages of outer surface strain variation, namely stable increase, fast increase and abrupt increase, which corresponds to the history of crack evolution. Crack grew stably in the initial stage under cycle of loading and a major crack is gradually formed. When the major crack size reaches a certain value, the propagation velocity of crack is accelerated fast and the critical size is reached in a short time. Eventually the tube fractured suddenly. The experimental findings will help us to gain new insight into the physical mechanism of fatigue and fracture of gun barrel and provide a possible method to evaluate health of gun barrel in service.

1. Introduction

When a large caliber rifled gun fires, the projectile is pushed along the gun barrel by the propellant combustion gas and ejected from the muzzle of the gun at high velocity towards a target. Typically, this firing process of interior ballistics lasts for a period of no more than 20 milliseconds. There are three important phenomena occurring in the closed space which is formed by the projectile, gun barrel and breechblock (figure 1). The first phenomenon is erosion which is induced by the propellant combustion gas of high temperature. Friction is the second phenomenon which occurs between the gun bore surface and the projectile with its rotating band. The third phenomenon is fatigue which is due to dynamic loading of high gas pressure, mechanical stress by barrel-projectile interaction and thermal stress produced by a large temperature gradient.
A combination of erosion, friction, and fatigue have damaged the gun barrel which has to be condemned and removed from service after firing hundreds or thousands of rounds. Gun bore erosion by high temperature combustion gas creates a chemically-affected zone and a heat-affected zone [1]. The microstructure and properties of the affected gun steel changes and makes the surface material harder and more brittle. The weakened material will be removed partially by friction between the high velocity projectile and gun bore. The result of erosion-assisted friction leads to an increase in bore diameter. This subsequently changes the condition of projectile-gun barrel interference fit. At last, the high pressure gas may leak between the projectile and gun bore which reduces the pressure and the projectile’s muzzle velocity. When the range and accuracy can not meet the requirements of fire, the gun barrel has to be condemned. Moreover, it is worth mentioning that cracks form on the bore surface and increase with continued firing (figure 2). Once micro-cracks appear on the lands and grooves, the free surface of a crack becomes partially exposed to the hot gas and thermal-chemical erosion also occurs. More seriously, these micro-cracks can grow, propagate, coalesce and eventually the crack network formation is completed.
Although 2D crack network is shown in figure 2, these cracks propagate along the radial direction from the inner surface to the outer surface of gun barrel. This means that cracks in the gun barrel is essentially 3D. After a certain number of rounds have been fired, the gun barrel undergoes cycles of dynamic loading. Once the depth of a major crack reaches the critical value it will break through the barrel wall under normal firing condition. The gun barrel fails in a sudden manner because of fatigue and this puts the crew in danger. Borescope and optical bore-mapping systems [2] are used to give a complete visualization of the bore’s condition. However, the depth of cracks can not be measured by these two kinds of apparatus. Typically, the thickness of a large caliber rifled gun barrel wall may be 50-100 mm. Unless the gun barrel is cut off (figure 3), the user can not observe the nearly uniform cracks around the inside of the barrel [3]. Therefore, in practice, the gun designer adopts a rule that the fatigue life of a barrel exceeds its wear life.

![Figure 3. Fatigue cracking in gun barrel section [3].](image)

Launching safety of gun barrel is a critical problem and has attracted extensive attention. Underwood and Troiano [4] gave a review of critical fracture processes in army cannons, including fast fracture, fatigue fracture, environmental fracture and coating fracture. Up till now, much research work has been done to avoid catastrophic fracture of gun barrel. However, the fracture problems are still important because the unlikely events of barrel fracture happen occasionally with modern guns all over the world. Figure 4 shows a schematic of health worsening process of gun barrel. It can be seen from figure 4 that the health of a gun barrel worsens gradually from the first round (Stage I, Point A to Point B) and deteriorates after firing a certain rounds (Stage II, Point B to Point C). Once a critical round (Point C) is fired, the health deteriorates sharply to the limit (Point E). Therefore, when the health index decreases from $h_{\text{max}}$ before the first round to $h_c$ after firing the limit round. In order to avoid sudden barrel fracture to the greatest extent possible, the barrel should be condemned when the health index decreases to $h_{\text{min}}$ ($h_{\text{min}} > h_c$). Therefore, it is time to solve the bottleneck problem of monitoring health condition of gun barrel and evaluating its launching safety. Wu et al. [5] presented a novel strain-based method, namely $\Delta$$\varepsilon$ method, for monitoring health and predicting remaining life of large caliber gun barrel. This method was adopted in our present work and a specially designed hydraulic testing system was used to investigate fracture of gun barrel under laboratory conditions.
2. Experimental

Fatigue tests were conducted using a MTS 809 Axial/Torsional Test System (figure 5). Two kinds of tube samples were tested. One has a pre-machined semi-circle crack with radius of 0.3 mm and the other is perfect tube. The inside diameter of the tube was 32 mm and the thickness of tube wall is 1.5 mm. As mentioned above, erosion-induced crack appears on the bore surface after firing few rounds, which provides a convenient condition for fatigue. Generally, a combination of firing and laboratory test is adopted to evaluate fatigue life of gun barrel. Therefore, a crack was pre-machined on the inside tube surface to simulate the erosion-induced crack. This indicates that the fatigue life is mainly determined by the period of crack growth and propagation.
Before fatigue test, a tube was completely filled of hydraulic oil and statically pressed to fracture. It can be seen from figure 6 that the tube fractured with a splutter and the hydraulic oil splashed on the surrounding plastic container when the load increased to -75.81 kN after 83 seconds. Therefore, fatigue tests were performed under compression-compression cyclic loadings. The maximum load and the minimum load were chosen as $L_{\text{max}}=-55$ kN and $L_{\text{min}}=-5.5$ kN in the fatigue tests, respectively. All tests were carried out at a frequency of 5 Hz with an R ratio of 0.1 ($R=L_{\text{min}}/L_{\text{max}}$). Two strain gauges were mounted on the central outside surface of the tube to monitor hoop strain and axial strain. A pressure sensor was used to monitor the pressure of hydraulic oil during test process. Figure 7 shows the monitored pressure of hydraulic oil during the initial period of about 710 seconds, which fluctuated between -68.4 MPa and -6.84 MPa. It can be seen from figure 7 that the hydraulic oil pressure kept quite stable.

![Figure 6. Statically pressed test.](image)

![Figure 7. Pressure cycle of hydraulic oil.](image)
3. Results and discussion

3.1. Test results

Figure 8 shows four samples under different conditions. Sample 1, sample 2, and sample 3 were perfect before test and sample 4 has a pre-machined crack. In static compression tests, the hydraulic oil was compressed to generate high pressure, which subsequently was exerted on the inside surface of the tube. Figure 8(b) shows large plastic deformation of sample 2 and the test was stopped deliberately. Sample 3 was compressed directly to brittle fracture (figure 8(c)). It was also found that large plastic deformation occurred before fracture. However, a much smaller plastic deformation was observed on sample 4 which failed due to fatigue fracture in figure 8(d).

![Figure 8](image_url)

Figure 8. Samples under different conditions: (a) original sample; (b) plastic deformation; (c) brittle fracture; (d) fatigue fracture.

The hydraulic oil pressure is 94.27 MPa at brittle fracture and 68.4 MPa at fatigue fracture. According to the third strength theory, the equivalent stress

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\sigma_{eq} = \frac{2pb^2}{(b^2 - a^2)}
\]

where, \(p\) is hydraulic oil pressure, \(a\) and \(b\) represents the inside and outside radius of the tube, respectively. The equivalent stress was computed as 1149.06 MPa for brittle fracture and 833.73 MPa for fatigue fracture. Sample 4 underwent 12807 cycles and fractured suddenly after about 43 minutes.

3.2. Discussion

Comparison between test results and actual gun firing indicates the following:

1) When a round is fired, if too high pressure was encountered for some reason, for example, abnormal combustion of propellant, the gun barrel is likely to fail due to large plastic deformation or brittle fracture. These two situations are similar to those with sample 2 and sample 3. When the equivalent stress exceeds the yielding strength, plastic deformation will surely occur and make the bore enlarge. If the equivalent stress reaches the ultimate strength, the gun barrel may fractured
suddenly. Once these two unpredictable situations happen the gun barrel has to be removed from the service.

(2) Typically, most gun barrels have fired hundreds or thousands of rounds before failure because of inaccuracy. Under normal firing condition, it is extremely unlikely that a gun barrel fracture occurs, which would be catastrophic. The erosion-induced cracks will grow and propagate along the radial direction under fatigue loading, which makes the strength of gun barrel decrease gradually with rounds fired. Once the residual strength of gun barrel decreases to a critical value, the equivalent stress of a normal round is high enough to cause barrel fracture. This situation is similar to that with sample 4. Figure 9 shows the crack path of the pre-machined crack propagating along the radial direction under fatigue loading. A crack initiated at the tip of the pre-machined semi-circle crack where high stress concentration existed. If the semi-circle crack was not pre-machined on the inside surface of tube, the initiation of a micro-crack would take a long time. In fact, erosion-induced micro-crack provide condition for later crack propagation under cycles of loading. Therefore, there is a consensus that the barrel fatigue life is mainly determined by the crack propagation life.

![Figure 9. Propagation of pre-machined crack under fatigue loading.](image)

(3) Gun barrel fracture must be eliminated from its entire service time because of damages to both the gun crew and the weapon. Many factors, such as propellant, projectile, fuse and gun barrel, have influences on the fracture of gun barrel. If a projectile explodes before it exits from the muzzle, the barrel will certainly break into fragments. The reason of this event may be attributed to failures of fuse and explosives in the projectile. However, it is impossible to predict gun barrel fracture induced from abnormal combustion of propellant, explosion of projectile in gun barrel. This can be avoided by proper design, manufacturing, inspection, storage and usage of fuse, explosive, projectile body and propellant. In fact, for the designer and user, the most important thing is to monitor health status of the gun barrel and change it opportunely in order to prevent fracture due to low residual strength under normal firing condition.
Figure 10 shows the hoop strain variation process of sample 4. The total strain time history can be divided into three stages. When the fatigue test begins, the strain increases gradually and reaches a certain value in a short time. Then it keeps very stable during stage I for about 2100 seconds. The strain begins to increase fast from variation point A during stage II. At 2556 second a turning point B appears where the strain increases sharply and exceeds the overrange limit of instrument. The tube fractured at 2588 second and stage III continued 32 seconds. It can be seen from figure 10 that stage II presents a prominent characteristic of strain rate increasing, which is clear to observe and used as a reminder to the barrel safety. Therefore, the fatigue test should be stopped intentionally in order to prevent tube fracture. This fatigue test result suggests that the barrel health can be evaluated based on the monitored outside surface strain. It should be noted that the outside surface hoop strain increases fast in the fatigue test in which the loading condition keeps unchanged. However, the outside surface hoop strain decreases with the rounds under actual firing condition [5]. We can mount the strain gauges on the barrel outside surface and monitor the strain from the first round. Strain of each fired round are stored and analyzed. When the strain is observed to decrease fast it is time for us to stop firing.

![Figure 10. Hoop strain time history of gauge.](image)

4. Conclusion

The focus of this paper has been to design and perform hydraulic tests based on analysis of damage and fracture mechanism of gun barrel. The following conclusions can be drawn by comparing the test results with real phenomena when a gun fires.

1. Permanent bore expansion, brittle fracture and fatigue fracture were reproduced by laboratory simulations.

2. Gun barrel health can be evaluated by monitoring the outside surface strain and when the strain changes rapidly the continued firing of gun must be stopped in order to prevent fatigue fracture.

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