Fatigue failure and launch safety assessment of gun barrel

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Abstract. Hundreds or thousands of projectiles have been fired through a gun barrel. Catastrophic fatigue failure of gun barrel due to cyclic loadings by the stresses induced by the combination of high pressure and temperature combustion gas, and projectile with the rotating band interaction with the bore surface, has not yet been understood. In this paper, laboratory hydraulic fatigue tests on simulated gun barrel were performed on MTS Land. The experimental results show that there is an inherent relation between crack propagation in thick-walled tube and the external surface hoop and axial strains. This fact suggests that fatigue failure of gun barrel should be likely prevented by monitoring the external surface strains of the gun barrel and stopping continued firing before a major crack growing up to the critical size.

1. Introduction
When a gun fires, combustion gas is generated after the solid propellant is ignited which results in a high pressure up to 250-700 MPa in a short period of no more than 20 ms. The gun barrel contains the high pressure combustion gas and guides the projectile in the intended direction (Figure 1). Under the action of combustion gas, the projectile with the rotating band is engraved by the forcing cone and later the rifling and accelerates along the gun bore, eventually exits from the muzzle at a high velocity. Typically, the temperature of combustion gas rises to 2200-3400 °C which induces a high temperature gradient at the bore. Two layers, a chemically-affected zone and a heat-affected zone, were formed during firing process [1, 2]. The microstructure of these two layers changes from the original structure and becomes harder and more brittle.

Figure 1. A schematic of gun barrel-projectile-propellant system.
The gun barrel operates in a harsh service environment. The hot combustion gas causes gun bore erosion (Figure 2). The combined action of the flow of high velocity gas passing over the surface and the friction between the gun bore and the rotating band moving through the bore leads to the gun bore wear. Wear and erosion result in an increase in bore diameter. The correct interaction changes between the rotating band and the worn gun barrel and gas leakage occurs between them reducing the gas pressure. The muzzle velocity, range, accuracy gradually decreases as wear increases. Impact wear occurs during the engraving process when the rotating band is pushed into the forcing cone and then the commencement of rifling in only a few milliseconds by the high pressure gas [3-6]. Therefore, the forcing cone and the commencement of rifling are the area of maximum wear because of the combination of thermo-chemical erosion by hot combustion gas and impact wear by the projectile. When the required accuracy can not be realized the gun barrel has to be condemned and removed from the service.

Fatigue fracture is another potential failure mode of gun barrel. Generally, the gun barrel is designed to fire as many rounds as possible before its condemnation due to unacceptable increase in diameter at the 1 in. from the commencement of rifling. For different types of guns, many hundreds or thousands of rounds have been fired during the service life. Therefore, fatigue is a major consideration in gun barrel design. As a rule, the fatigue life of gun barrel should exceed its wear life because fatigue fracture happens catastrophically and pose a serious threat to gun crew’s safety. Micro-cracks form on the bore surface as the result of the firing process, some normal to the surface and some parallel with the surface. Gun bore surface erosions provide large numbers of stress concentration zones where the surface cracks initiate from the erosion surface (Figure 3). Complicated stresses occur at the inner portion of the gun barrel. The tensile hoop stress and shear stress caused by high pressure gas, the contact stress generated by the rotating band, and the thermal stress induced by the acute temperature gradients, are combined to make these micro-cracks grow and propagate along the radial direction. When the critical size of a major crack is reached, the gun barrel can not bear the gas pressure and fracture in a catastrophic manner under normal firing condition. In order to improve fatigue life of gun barrel, autofrettage has usually been applied to introduce favorable residual compressive stresses in the region of high tensile stresses and decrease susceptibility to inner cracking.

Figure 2. Wear and erosion at the forcing cone and the commencement of rifling.

Figure 3. Cracks on the bore surface by the presence of erosions.
Fatigue of gun barrel has long been an important issue [7-9]. There are great difficulties to investigate fatigue behavior of gun barrel. First, the gun barrel is physically a thick-walled tube. The erosion-induced micro-cracks initiate on the bore surface and their propagation in radial direction from the inner surface to the outer surface are hard to detect. Second, growth of cracks in thick wall of gun barrel are determined by many factors under different firing conditions. From the viewpoint of launch safety of gun barrel, it needs continued insight into the fatigue behavior of gun barrel. Traditionally, fatigue life test of gun barrel is a combination of firing and laboratory test. A few rounds have been fired to generate initial micro-cracks on the bore surface mainly by the erosion. Then the section of gun barrel with the forcing cone and the commencement of rifling is cut for laboratory tests by using hydraulic fatigue testing facility. In this paper, a specially developed hydraulic testing system was used to carry out fatigue tests on a simulated gun barrel with a prepared defect on the inner surface. The primary experimental results suggest a possible method to monitor the crack propagation by using hoop strain on the outer surface of the gun barrel and fatigue fracture can be avoided at a certain time when the strain begins to change rapidly.

2. Experimental

Sample with inner diameter of 32 mm were made of No. 45 carbon steel. A weakened section with thickness of 2.8 mm and length of 20 mm was chosen for preparing a defect (length×width×depth: 10 mm×0.3 mm×0.5 mm) on the inner surface along the axial direction (Figure 4). Fatigue tests were performed on MTS Landmark under compression-compression cyclic loadings of constant stress amplitude (Figure 5). The stress ratio R=0.1 was given and the frequency of the repeated compressive load is 5 Hz. Two strain gauges were mounted on the outer surface to measure hoop strain and axial strain. Before testing, the sample tube was filled fully with No. 46 oil and leakage of the system should be checked for keeping the pressure stable during the whole tests. A pressure transducer was adopted to measure the oil pressure. The external strains and oil pressure data were monitored and stored in the computer for later analysis. Xradia 520 Versa was used to inspect the crack propagation nondestructively.

Figure 4. Sample for fatigue tests.
3. Results and discussion

Sample 1 was manufactured without prepared defect which simulates the new gun barrel. Sample 2 has a prepared defect of 10 mm×0.3 mm×0.5 mm which simulates a worn gun barrel which has fired a number of rounds. Sample 1 was pressed to fracture by the oil pressure when the load rises to 122 kN, whereas sample 2 fractured at 111 kN (Figure 6). It can be deduced by comparison of two samples that a worn gun barrel may fracture under a smaller pressure. For example, a new gun barrel can operate safely by using high charge zone. After some rounds have been fired, the interaction of wear and fatigue caused damage to the barrel. If high charge zone is used, the barrel could not bear the gas pressure and fracture suddenly. Therefore, a low charge has to be adopted for safe firing. It can be seen from figure 6a and figure 6b that the fragment of sample 1 broke the plastic shield. In figure 6c and figure 6d it is observed that fracture occurred at the weakened area with the prepared defect.
Sample 3 was tested with the maximum load of 45 kN and the minimum load of 4.5 under compressive-compressive cyclic fatigue loading. After 24188 cycles a crack broke through the tube wall and the oil ejected from the open crack (Figure 7a). When the maximum load decreases to 35 kN, sample 4 eventually failed after 90057 cycles. The average incremental growth of crack is 0.0964 μm per cycle of sample 3 and 0.0249 μm per cycle of sample 4. Comparison between sample 3 and sample 4 shows that oil pressure have great influences on the fatigue life. This fact suggests that a gun barrel will fire more rounds under low charge zone condition. Crack initiated at the prepared defects and propagated from the inner surface along the radial direction. Sample 5 was also tested with the maximum load of 45 kN. For reference, the test on sample 5 was stopped after 21356 cycles and detected for observing the crack propagation (Figure 7c). The average incremental growth of crack is 0.0219 μm per cycle of sample 5. Comparing sample 3 and sample 5, it is found that initiation of crack at the prepared defect consumes a number of cycles. At this first stage, propagate rate of the crack is too small. However, the propagate rate rises faster and faster with cycles increasing. For example, the average incremental growth of crack is estimated as 0.6555 μm per cycle if the crack breaks through the tube wall after the same cycle as the sample 3. This fact shows that the failure of the tube can be avoided by stopping the test in time, which suggests that a gun barrel should be stop firing after a number of rounds in order to prevent fracture.

Figure 7. Crack propagation in the tube wall under different fatigue loadings.

Sample 6, sample 7, sample 8, sample 9, sample 10 and sample 11 were tested with the maximum load of 55 kN. After 8173 cycles the crack broke through the tube wall of sample 6. Therefore, tests of sample 7 to sample 10 were stopped after 6329 cycles, 5003 cycles, 4003 cycles, 3004 cycles and 2004 cycles. Crack propagation of these five samples were inspected and shown in Figure 8. It is observed that crack formed at the prepared defect after 2004 cycles shown in Fig. 8e and propagated as far as 78.7 μm. The average incremental growth of crack is estimated as 0.1012 μm per cycle at the initial stage, whereas that of the end stage is about 0.3008 μm per cycle. Obviously, the crack propagates faster and faster during the entire testing process with the increase of cycles. Meanwhile, comparison of sample 3, sample 4 and sample 5 shows that the tube has different fatigue life under different loadings. For given the same stress ratio, the higher the maximum load, the shorter the fatigue life. This verifies again that a gun barrel has a shorter service life using high charge zone but longer life with the low charge zone.

Figure 8. Crack propagation in the tube wall after different cycles.
Hoop strain on the outer surface of the tube was measured during the whole test as shown in Figure 9. It is observed that the whole changing process of hoop strain can be divided into three stages. The hoop strain changes slowly during stage I before point A. In stage II, the hoop strain increases faster and faster. Once point B is passed, the hoop strain rises sharply and overloads when the crack broke through the tube wall. Therefore, the test must be stopped at the end of stage II, namely before point B. It is found that the hoop strain fluctuated because of cyclic loading of oil pressure (Figure 10). However, this does not affect the changing trend of the hoop strain.

In general, gun barrel is a thick-walled tube. For example, the thickness of a 155 mm gun may be 50-70 mm. Erosion and wear occur on the bore surface. Micro-cracks form on the inner surface randomly. At a certain area of high stress concentration, a surface crack propagates along the radial direction. After firing a number of rounds, this crack grows and its size increases. However, it is difficult to detect a short macro-crack of no more than 2 mm without special apparatus. In fact, the propagation process of crack is also divided into three stages. At the first stage, the incremental growth of crack per cycle is small and increases slowly. At the second stage, the crack grows faster and faster and the propagating rate of crack increases largely. At the third stage, the crack size increases sharply and eventually breaks the tube wall in a very short time. Therefore, there should exist an inherent relationship between crack propagation and external surface strain (hoop strain and axial strain). Although crack initiation on the inner surface and propagation in the thick-wall barrel is difficult to detect, the external strains on the barrel outer surface are easy to measure. Hence, a possible method to feel crack propagation in the gun barrel is to monitor the external surface strain based on inverse problem solution.

Launch safety of gun barrel has long been an important issue and is yet not well understood. Many types of guns all over the world have occurred fracture failure and sometime caused severe injury or death to the gun crew (Figure 11). Several U.S. 175 mm gun barrels failed during firing in Vietnam. For example, a gun barrel No. 733 fractured catastrophically in April 1966 which was manufactured from a high-strength steel alloy. Brittle fracture of the 175 mm gun was reported to be due to high strength but lower toughness of the steel. 373 rounds at a nominal pressure of 345 MPa and 227 rounds at a pressure of 152 MPa have been fired. In fact, at the time of failure, the gun barrel broke into 29 pieces with the final round generating a nominal pressure of 345 MPa. Examination of the gun barrel fragments revealed no evidence of overpressure. The ammunition being fired at the time of the failure was tested and nothing abnormal was found. A 0.94×2.79 cm semielliptical crack located near the breech end of the gun barrel was formed from the initial micro-crack on the inner bore generated by the hot combustion gas. Therefore, there are two possible reasons for gun barrel fracture. One is that the propellant burns abnormally leading too high combustion gas pressure and the gun barrel cannot bear the dynamic loading. The other is that a number of micro-cracks on the bore surface propagate in the thick-wall gun barrel and a major crack reaches a critical proportion which results in a sudden fracture even if the gun
barrel operates under normal gas pressure. In comparison with the former, the latter is an ordinary case in the service life of gun barrel. All gun barrels have large number of cracks inside their thick-wall because of cyclic loading (one round = one loading cycle) during the service time. Therefore, launch safety of gun barrel should be taken seriously.

Figure 11. Gun barrel fracture.

The autofrettage process has been applied to gun barrel in order to introduce favorable residual compressive stresses at the inner portion of the barrel wall. It is known that the maximum tensile hoop stress as well as the maximum von Mises equivalent stress occur at the gun bore. Although the combination of compressive stress and the hoop tensile stress is beneficial to gun barrel and decrease the susceptibility to inner cracking, erosion and wear of bore surface will gradually weaken the effect of autofrettage. Levy et al. [10] shows that the combination of lower autofrettage and multiple finite length or infinitely long erosions reduces the fatigue life of the gun barrel. Therefore, fatigue life should be considered in the design, manufacturing, usage and maintenance of both non-autofrettaged and autofrettaged gun barrel. In a word, the most effective way to prevent catastrophic fracture of gun barrel is to stop firing and remove the barrel from service before a major crack reaches the critical size, which can be most likely realized by thoroughly understanding the relation between crack propagation and external hoop and/or axial strains on the outside surface of the gun barrel.

4. Conclusion

There is a great deal of interest in preventing the gun barrel in service from catastrophic fatigue fracture failure. Launch safety of gun barrel has long been a key issue in the interior ballistics and has not yet been solved. In this paper, a series of specially designed tests were carried out on simulated gun barrel by hydraulic fatigue testing on the MTS Landmark. The conclusion can be drawn as follows.

(1) The maximum stress or the average stress has great influences on the fatigue life of the sample tube. The higher the maximum pressure, the shorter the barrel fatigue life. This fact suggests that the high charge zone leads to short fatigue life of the gun barrel in actual firing condition.
(2) Under the same cyclic loading the sample tube with prepared defect has fewer cycles before failure when compared with the tube without any prepared defect. This means that erosion-induced cracks will propagate in the radial direction and grow up to a critical size, which results in the reduction of strength and toughness.

(3) Relation between crack propagation and hoop and/or axial strain is confirmed by the experimental results. This relation can be used to investigate the crack propagation in thick-wall barrel by monitoring the external surface strains. Therefore, the fatigue fracture and launch safety of gun barrel should be prevented from its service life.

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