19th International Symposium of Ballistics, 7–11 May 2001, Interlaken, Switzerland

TEMPERATURE AND HEAT TRANSFER AT THE COMMENCEMENT OF RIFLING OF A 155 mm GUN

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The temperature and heat transfer per round has been measured at the bore surface of a 155 mm AS90 extended range ordnance. The ammunition was fired with and without wear-reducing additive and the measurements were made using an eroding-type surface thermocouple having response time of about a microsecond. The heat transfer was computed from the measured temperature-time curves. It was found that the wear-reducing additive gradually reduced the surface temperature fluctuation from about 950°C to about 600°C, and reduced heat transfer per round from about 950 kJ/m^2 to about 600 kJ/m^2, over a period of fifty rounds. From these measurements an assessment was made of the wear rate, the number of rounds to cook-off, and the increase in barrel fatigue life.

INTRODUCTION

The paper describes work carried out to support the assessment of new ammunition for the 155 mm, 52 calibres AS90 extended range ordnance. In particular, the paper describes experimental work to determine the temperature and heat transfer at the bore surface of the barrel at or near the commencement of rifling. From these measurements it was possible to assess the improvements in gun barrel erosion, the number of rounds to cook-off, and the barrel's fatigue life.

Two charge types, designated *N* for normal and *M* for modified, were fired using new barrels for each. Charge *N* was a full charge giving a muzzle velocity of about 940 m/s and charge *M* attained the same muzzle velocity and maximum pressure but contained a wear reducing additive. Over 100 rounds of each were fired in the trial.

INSTRUMENTATION

Fast response, eroding type, thermocouples have been available from ASEA in Sweden and are currently available from the Medtherm Corp., USA. In this paper only the results from the ASEA thermocouple, Fig. 1, are described. A Ni-Cr centre pin is separated

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by a 2 µm dielectric from a Ni-Cr outer tube. The whole is mounted in a 4.5 mm diameter tapered steel tube. The hot junction is formed at the butt-end by abrading or scratching the butt-end to transfer a thin smear of metal from the inner pin to the outer tube. As the surface wears the hot junction continuously reforms at the new surface and maintains a thickness of about 2 µm. The maximum temperature rise is 600°C (continuous), 1500°C (flash), and the rise time (10% to 90%) is 1 µs. Such thermocouples are ideal for measuring the temperature at the bore surface of a gun where erosion rates are usually between 1 µm per round and 100 µm per round.

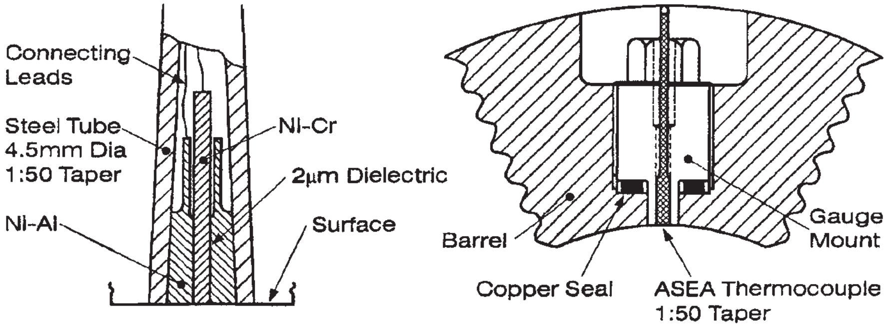

Fig. 1. Eroding-type thermocouple (left) and the method of fitting into the barrel (right).

The method used to fit the thermocouple into the barrel of a 155 mm gun is shown in Fig. 1 (right). The tapered thermocouple is pressed into a gauge mount using a pressure similar to that expected in the gun. The gun mount was then screwed into the barrel and seals onto copper washers. The copper washers were adjusted in thickness to ensure the thermocouple's surface did not protrude into the barrel. This was checked with a boroscope. The thermal diffusivity of the thermocouple is $7.3x10^{-6}$ m^2/s compared to $9x10^{-6}$ m^S/s for typical gun steel; consequently the thermocouple will record temperatures that are about 11% greater than those in typical gun stee1 subject to the same heat input.

The thermocouple signals, about 40 µV/°C, were amplified using a RS amplifier INA131AP, which has a fixed gain of 100 and a frequency response from dc to 70 kHz. About 3 m of compensating cable connected the thermocouple in the barrel to the amplifiers, which were kept inside an insulated box that formed the cold junction. The amplifier output signals passed down about 55 m of 50 Ω BNC cable to a Nicolet digital oscilloscope that was set to trigger when the thermocouple temperature exceeded about 150°C. The instrumentation was calibrated using a dc milli-voltmeter to input a known voltage at the thermocouple and the gain was checked from the response at the oscilloscope. The signals were stored on disk and were subsequently transferred to a digital computer for processing and graphing. The numerical method used to process the measured temperature-time curves and to compute the heat transfer is described in reference [1].

PROCEDURE

Two new barrels were used. One fired Charge *N*, a normal propellant without any wear-reducing additive, whereas the other fired charge *M*, modified by the addition of a wear-reducing additive. Each charge attained a maximum pressure of about 350 MPa and a muzzle velocity of about 940 m/s. Two trials were made with each barrel. In the first trial the barrels started at ambient temperature but in the second trial they were pre-heated to about 120°C. The heated section of barrel was about 2 m in length near the commencement of rifling. Each trial consisted of about fifty rounds fired at a rate of about one round every six or seven minutes. Before each session two “warming rounds” were fired. Only seventeen of the 200 signals were not successfully recorded, usually because the hot junction had not properly re-formed.

RESULTS

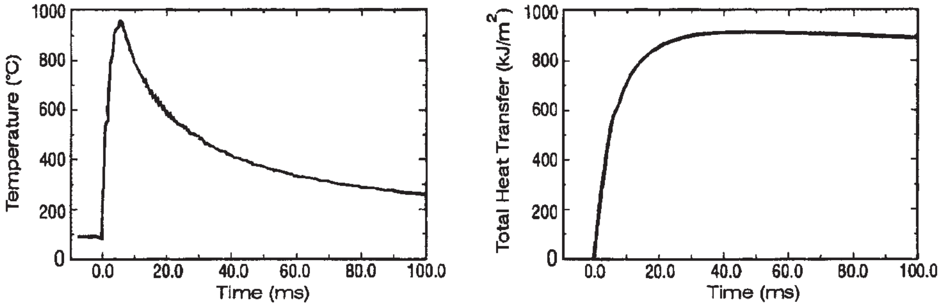

Fig. 2. Typical temperature-time curve measured at the commencement of rifling (left) and the corresponding heat transfer-time curve (right).

A typical surface temperature measurement at the commencement of rifling is illustrated in Fig. 2 (left). On some signals 50 Hz background noise was present but this was removed numerically. A slight increase in signal noise sometimes occurred between about 15 ms and 50 ms, as shown in Fig. 2, and was probably caused by the sudden movement of the thermocouple leads as the gun recoiled. The maximum temperature in this case reached 950°C and occurred about 5 ms after the thermocouple was uncovered by the passage of the projectile. Shot exit occurred at about 15 ms. The temperature-time curve was processed to determine the heat transferred, Fig. 2 (right), and shows that the total heat transfer rises to 900 kJ/m^2 at about 40 ms.

Maximum Bore Temperature

The maximum temperature of the bore surface when firing charge *N* and charge *M* in unheated barrels is shown in Fig. 3 (left). The maximum bore temperature remained

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steady at about 950°C for the entire 50 rounds when firing the normal ammunition. Some round to round variation, amounting to a standard deviation of 53°C is apparent. When the modified ammunition was fired the maximum bore temperature was initially 950°C, similar to that of the normal charge, but as the trial continued the maximum temperature declined steadily to about 600°C afrer 40 or 50 rounds. Apparently the wear reducing additive did not have an immediate effect but built-up steadily from round to round. This suggests that the additive formed a thin surface coating on the bore of the barrel that increased in thickness as more rounds were fired. An overnight break in the firing did not disturb the degree of protection.

When the two charges were fired into preheated barrels, Fig. 3 (right) the maximum bore temperature of the normal ammunition tended to increase throughout the trial from about 1000°C at the start to about 1200°C at the end. Charge *M*, however, showed an impressive reduction. The first round fired gave a maximum bore temperature of about 910°C but almost immediately the maximum bore temperature declined so that after about 10 rounds it was only about 650°C. For the next 30 rounds the maximum bore temperature remained steady at this value before declining further to about 500°C after which it quickly increased to about 750°C. This behaviour suggested that the wear-reducing additive adhered better to a hot surface and thus the built-up of protection was faster for the pre-heated barrel and resulted in foll protection after only 10 rounds. After about 40 rounds the protective layer appears to increase again and then, becoming too thick was partially removed from the surface causing the observed rise in the maximum bore temperature. Had the trial continued, it seems likely that the maximum bore temperature would have reduced again to about 600°C. For much of these two trials charge *M* was some 450°C cooler than charge *N*.

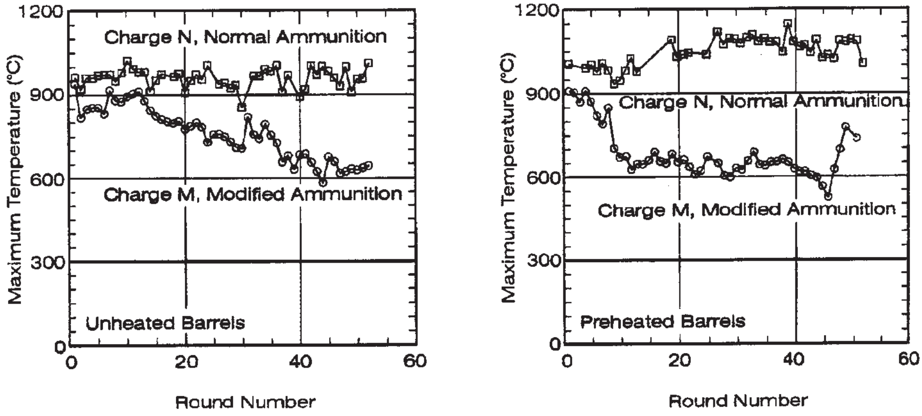

Fig. 3. Maximum bore temperature for charge *N* and *M* fired in unheated barrels (left) and in barrels preheated to about 120°C (right).

Total Heat Transfer

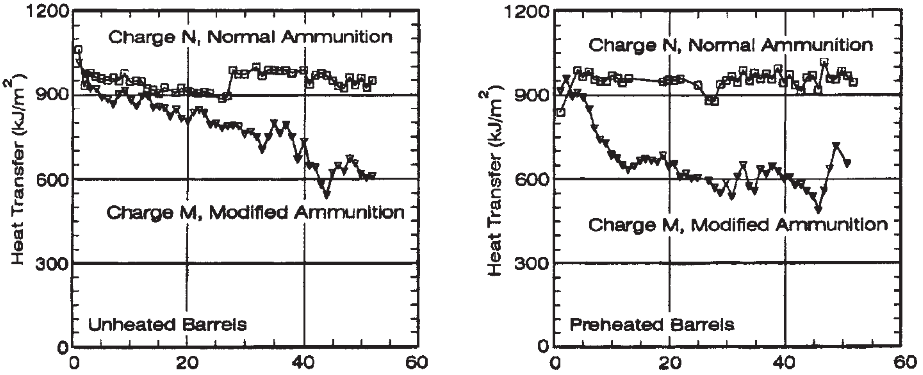

Fig. 4. Heat transfer per round for charge *N* and *M* fired into unheated barrels (left) and into barrels preheated to about 120°C (right).

The heat transfer per round, Fig. 4, reflects the results illustrated in Fig. 3. For charge *N* in the unheated barrel, Fig. 4 (left), the total heat transfer per round remained substantially constant at about 950 kJ/m^2 but for charge *M* it declined steadily from about 1000 kJ/m^2 to about 600 kJ/m^2 after 50 rounds. When fired into preheated barrels, Fig. 4 (right), the heat transfer per round of charge N again remained substantially constant at about 950 kJ/m^2. For modified charge, charge M, the heat transfer per round declined from about 950 kJ/m^2 to about 650 kJ/m^2 after 10 rounds and thereafter remained steady until after 40 rounds it started to decline, reaching about 500 kJ/m^2 after 45 rounds and then suddenly increasing to about 700 kJ/m^2. Again, this behaviour suggested that the wear reducing additive adhered better to a hot surface and thus the built-up of protection was faster for the pre-heated barrel and resulted in full protection after only 10 rounds. After about 40 rounds the protective layer appears to increase again and then becoming too thick was partially removed from the surface causing the observed rise in heat transfer.

ASSESSMENT

It is well known (2) that wear reducing additives work primarily because they reduce the bore temperature and heat transfer and the observed relation between wear per round and the maximum bore temperature has been confirmed by theory (3). Wear-reducing additives radically increase the wear-life of a gun barrel. However, there are other advantages related to their use. The reduced heat transfer per round means that many more rounds may be fired before a barrel reaches the self-ignition (cook-off) temperature of the ammunition. Also, the reduced temperature fluctuation at the bore surface reduces the thermal stress fluctuation and thus reduces the depth of the initial crack. A smaller initial crack length increases the number of rounds that must be fired before fatigue failure occurs and thus it increases the barrel's fatigue life.

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Wear Life

To illustrate the reduction in wear caused by the additive some data relating to standard cordite (SC) may be used, Fig. 5 (left). The vertical scale of Fig. 5 is the observed wear rate of gun barrels firing propellant SC (4) and the horizontal scale is the maximum bore temperature calculated by the relatively simple method described in (3). For charge *N*, the normal ammunition, the maximum temperature was about 1000°C, the bore *d* is 0.155 m, and the muzzle velocity, C_m, is 940 m/s, thus from Fig. 5 the expected wear rate is 18 microns per round. For charge *M*, the ammunition with wear reducing additive, the maximum bore temperature is about 600°C so the expected wear rate is 1.6 microns per round. Thus the wear-reducing additive increases barrel life by about 10 times.

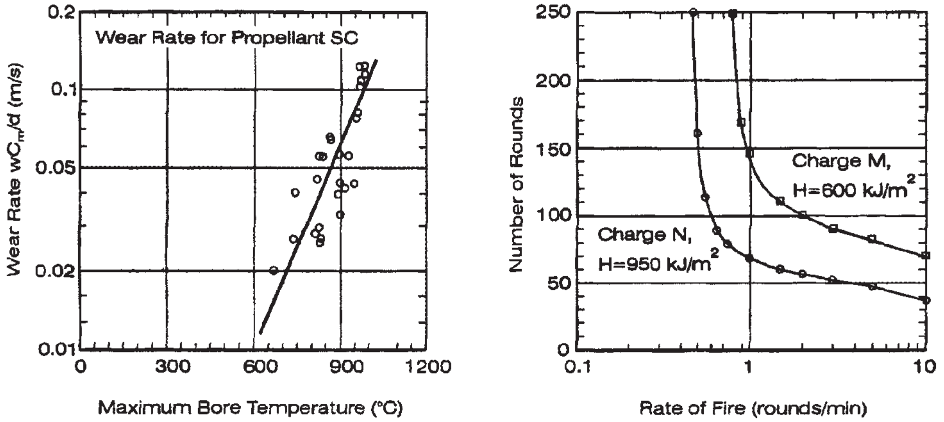

Fig. 5. Wear characteristics of propellant SC (left) and influence of rate of fire on the number of rounds to cook-off when firing charge N and M (right).

Cook-Off (Self-ignition)

Methods of computing gun barrel temperatures have been described by many workers (5)(6) but the method used here is that described in (7) with the exception that the heat input per round is taken to be the measured values for the 155 mm gun rather than the theoretical values. The bore temperature fluctuates from an initial temperature, often called the quasi-steady temperature, to a maximum temperature, and then returns to its quasi-steady temperature after a few seconds. The quasi-steady temperature is, therefore, the long-term bore temperature that transmits heat to the ammunition when it is loaded and it is assumed that cook-off occurs when the quasi-steady bore temperature reaches a critical temperature. In this case the critical temperature was assumed to be 180°C. It was also assumed that the gun fired at a constant rate in the range 0.5 to 10 rounds per minute. The time taken and number of rounds fired before the barrel reached its cook-off temperature was determined. For charge *N* the heat input per round was taken to be 950 kJ/m^2 and for charge *M* it was taken to be 600 kJ/m^2. The results are shown in Fig. 5 (right).

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For low rates of fire, below about 0.48 round/min for charge *N*, the quasi-steady temperature never reached the cook-off temperature and there was no thermal limit to the number of rounds than could be fired. As the rate of fire was increased the number of rounds to cook-off became finite and reduced to 53 rounds at about 3 rounds/min. For charge *M* there was no thermal limit for rates of fire less than 0.78 rounds/min (an improvement of 63%) and at 3 rounds/min cook-off occurred after about 83 rounds (an improvement of about 57%).

Fatigue Life

If the temperature fluctuation at the bore is caused by an impulse of heat then the temperature fluctuation at any distance x from the surface is given by (8)

$$\Delta T = \sqrt{\frac{2}{\pi e}}\,\frac{H_\infty}{\rho C_v x} \tag{1.1}$$

The thermal stress caused by this temperature fluctuation is

$$\sigma = \frac{E\alpha\Delta T}{1-m} \tag{1.2}$$

This thermal stress causes a crack of length x= a_C when the stress intensity, $Q\sigma\sqrt{(\pi a_C)}$ equals the critical stress intensity, K_{ic}, for the gun steel. Thus from Equ. 1.2 and 1.3 the crack length is

$$a_c = \frac{2}{\pi}\left[\frac{QE\alpha}{K_{ic}(1-m)}\,\frac{H_\infty}{\rho C_v}\right]^2 \tag{1.3}$$

The initial crack length is proportional to the square of the heat input per round and so it is expected that the crack length when firing charge *M* will be reduced to $(600/950)^2$ = 0.4 of the crack length when firing charge *N*. From the Paris law the fatigue life of a barrel is inversely proportional to the square root of the initial crack length and thus we might expect the fatigue life of charge *M* to 58% greater than the fatigue life of charge *N*.

CONCLUSIONS

Charge *M*, which contained the wear-reducing additive, reduced the maximum bore temperature from about 950°C to about 600°C in an unheated barrel and the heat transfer per round reduced from about 950 W/m^2 to about 600 W/m^2. The reductions observed in the preheated barrel were even greater. The reduction in bore temperature is expected to reduce wear rate from about 18 microns per round to about 1.6 microns per round giving an increase in barrel wear life of about 10 times. The reduced heat transfer is expected to increase the number of rounds to cook-off from about 53 to about 83 at 3 rounds/min; an increase of 63%. The reduced temperature fluctuation at the bore is expected to reduce thermal stress and initial crack length resulting in a 58% increase in fatigue life.

ACKNOWLEDGEMENT

The author would like to thank Ministry of Defence and Vickers Shipbuilding and Engineering Ltd (VSEL) for permission to publish this work and also the many people in both organisations who have assisted in various ways.

NOTATION

a_c	crack length, m	C_v	specific heat, J/kgK
E	modulus of elasticity, Pa	H_∞	total heat transfer, J/m^2/rnd
K_{ic}	critical stress intensity factor, Pam$^{0.5}$	m	Poisson's ratio
Q	geometrical factor	x	distance from surface, m
α	coefficient of thermal expansion, K^{-1}	ΔT	temperature difference, K
ρ	density, kg/m^3	σ	stress, Pa.

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