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Measurement of 9 mm cartridge case external temperatures and its forensic application

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ABSTRACT

The external temperature of the cartridge cases of 9 mm parabellum ammunition during the firing sequence was measured by a series of methods. Using a thermal imaging camera was the most successful method and showed that aluminium alloy cases reached higher temperatures than did brass cases. Peak temperatures for brass cases were 336 K at the case mouth after 1.2 ms and 331 K at the case base after 2 ms. Corresponding temperatures for aluminium alloy cases were 363 K at the mouth after 0.8 ms and 372 K at the base after 1.2 ms. These times at temperature would not be sufficient to destroy any DNA residues left on the case. Measurement of the DNA of fired cartridges showed that DNA deposited on the cartridge case before firing was not affected by the temperatures reached during the firing sequence. Estimates of temperatures to be found in pure aluminium and mild steel cases were made, these indicating that pure aluminium would give higher temperatures than aluminium alloy and steel a lower temperature than for brass.

It would be helpful to investigators of gun-related crimes if it were possible to collect DNA samples from the outside of fired cartridge cases found at a crime scene. Szibor et al. [1] studied the mitochondrial DNA traces on personal firearms used by 10 police officers, comparing these to saliva samples donated by the officers. They found that of the 50 unfired cartridge cases, 18% gave “reliable identifications”, 14% gave a “nearly sufficient result”, 8% “mixed stains” and 60% a “completely non-sufficient” result. These results did not consider the thermal cycle undergone by the cartridge case when it is fired. Work by Spear et al. [2] on a series of cartridges showed that, of 24 unfired cartridges, 2 bloody fingerprints gave “useable” or “identifiable” prints, 3 oily fingerprints gave “useable” or “identifiable” prints whilst none of the sweaty fingerprints (likely to be the most common at crime scenes) gave “useable” or “identifiable” prints. Their work on the 24 fired cartridges showed 1 “useable” print, taken from a bloody fingerprint. DNA testing carried out after fingerprint processing, using an amplification technique (Applied Biosystem Profiler Plus STR reagent kit) only produced 3 profiles, all obtained from bloody fingerprints, 2 from unfired cartridge cases and the other from a fired case. All these results indicate that the collection of DNA from the external surfaces of cartridge cases is difficult and that the thermal cycle undergone by the case during firing may have an effect on biological traces left on the case.

Against this background a programme to develop coatings which aim to capture DNA from the user more extensively and donate unique nanotags to the user has been started. The association of DNA and nanotags will be stronger evidence for the presence of an individual than the DNA evidence alone. These coatings are based on pollen coated with oxides such as TiO_2 and ZrO_2 produced by the reaction of alkoxide vapours with the surface OH groups on pollen. It is still necessary to determine the fate of DNA, whether associated with a coating or not, after firing and to relate this to the temperature cycle. Another feature appearing to affect the collection of DNA from cartridge cases is the roughness of the contact surface and the pressure applied by the person on to the surface. Pulley et al. [3] showed that DNA was most successfully recovered from the slide serrations of pistols rather than from smooth surfaces such as those of cartridge cases. This confirmed the earlier results of Szibor et al. [1] who were more successful in collecting DNA from the trigger of a pistol than from a cartridge case. Work by Xu et al. [4] showed that pick-up of DNA was increased when brass was knurled to pattern the surface.

The survivability of DNA when heated has been studied in the context of the identification of fire victims. Calacal et al. [5] were able to identify two fire victims from the DNA taken from bone samples where the bodies had been interred for three months after the fire. They made no estimate of the likely temperatures that the

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bones had reached. Holden et al. [6] examined the femoral bones of a car fire victim and, by comparison with their work on bones heat treated in the laboratory [7], estimated that the outer cortical bone had attained a temperature of 1273–1473 K whilst the inner cortical bone had reached a temperature of at least 573 K. Assuming that the building fire of [5] was of roughly similar severity to the car fire of [6] this would indicate that identification of DNA from remains or artefacts, including cartridge cases, could be possible even if temperatures achieved by the artefacts were to substantially exceed 500 K.

Investigations of the heat transfer from burning propellant have normally concentrated on calculation of the gun tube bore temperature, a factor helpful to gun designers in their understanding of wear mechanisms in the gun. Meysmans [8] measured, using a special calorimeter and cartridge cases that had just been ejected, the heat transferred to the cartridge during firing. From a sample of 30 cases he showed that heat transfer to be around 194 J/case. He thus calculated the average temperature of the case to be 348 K, assuming a cartridge case mass of 6.8 g and a heat capacity of 380 J/kg K. However, he could not calculate the temperature distribution as a function of position in the case. The measurement of temperature of the cartridge case is particularly difficult as the whole process of firing is complete in less than 2 ms and the cartridge case is externally invisible for the first 0.3 ms and only partially visible for the next 0.4 ms. Allsop and Toomey [9] describe in greater detail the firing sequence of small arms, an event which is complete within 1–2 ms.

Since the heating of the cartridge case will be a process of unsteady state heat transfer the temperatures achieved will be a function of the case material thermal diffusivity as well as the case geometry and the nature and quantity of propellant used. Thus the material (aluminium, brass or steel) of the case will affect the case temperature and thus, possibly, the survivability of any DNA captured.

The aim of the present work is to present measurements of the case temperatures as a function of time immediately after firing in order to relate this to the temperatures at which DNA is likely to be damaged.

1. Materials and methods

The ammunitions were of 9 mm × 19 mm parabellum type using a double base (nitroglycerine and nitrocellulose) propellant and were fired remotely from a Browning pistol. The cases were either of cartridge brass (70 weight per cent Cu and 30 weight per cent Zn) or of aluminium alloy (4.75 weight per cent Cu, 0.52 weight per cent Mg, 0.69 weight per cent Mn, balance Al, approximating to 2014 composition). All cases were produced by deep drawing with no mouth annealing, so the whole case was in the as cold-worked condition. The firing sequence was recorded by high-speed video camera (Phantom).

1.1. Estimation of temperatures

Temperatures were measured or estimated by three methods.

1.1.1. Infrared thermal camera

Infrared thermography, using 8–9 μm radiation, was carried out using a Flir ThermaCAM® SC3000 system, which has a reported ability to detect surface temperature variations in components of 20 mK at 303 K. The infrared camera was set to scan at 250 Hz. Further details of the camera system can be found in [10]. The SC3000 system was placed on the tripod at about 1 m away on the right side of the firearm in order to capture the cartridge cases ejecting from the chamber. The recording was setup and controlled using a PC with the ThermaCAM® software. The recording was triggered by the user just before and after the firing was complete. Prior to firing tests, the emissivity for the aluminium and the brass cartridge cases was calculated by measuring the surface temperature of the cartridge cases using a calibrated thermocouple and found to be 0.8 for the aluminium cases and 0.76 for the brass cases.

1.1.2. Thermocouples

A K-type nickel–chromium thermocouple was connected to a calibrated Fluke-51 temperature meter. After the cartridge case was ejected from the chamber it was picked up using a sharp point forceps and the temperature was measured by placing the tip of the thermocouple on the surface of the cartridge base. The first temperature measurement was taken 15 s after the firing and at 5 s intervals thereafter for 1 min. The temperature at the early times just after the firing was calculated by extrapolating the temperature data back to 0.2 ms.

1.1.3. Micro-hardness measurements

Micro-sections of cartridge cases were prepared and the hardness measured using an Indentec HWDM-7 micro-hardness measurement system with a 100 g load. The hardness of interest was at the inner surface of the case where the temperature was at its highest. The closest measurement was taken at 20 μm from the inner surface.

1.2. DNA measurements

DNA was extracted from 10 samples, which had been taken from cartridges that had been knurled in the rim area [4] and fired, using the Qiagen EZ1 investigator kit (Qiagen, Crawley, UK). Material from the test samples was removed by sonication of the cartridge in a microcentrifuge tube containing G2 buffer prior to following the manufacturers instructions. The DNA sample was then concentrated to a volume of 25 μl using a Microcon microconcenrator (Millipore, Cork, Ireland). Two aliquots of each extract were then amplified using Amp*Fl*STR® SGMPlus® STR kit as described in Cotton et al. [11] and Whittaker et al. [12] except that a final reaction volume of 25 μl was used. Amplified products were separated using an AB 3130 genetic analyser (Applied Biosystems, Warrington, UK) and the results were scored using ABPrism Genemapper™. Alleles were reported only if observed in both duplicate amplifications in accordance with Whittaker et al. [12]. Sample success was scored on the basis of percentage profile achieved from the sample donor.

2. Results

2.1. Video evidence

Frames taken from the video of the firing show that the cartridge case begins to be visible at about 0.4 ms into the firing sequence and is clear of the gun by 1.2 ms. These times were similar to those reported in the firing sequences of Allsop and Toomey [9].

2.2. Thermal imaging evidence

The temperature images at suitable times were extracted following the infrared thermal recordings for aluminium and brass cartridge cases, as shown in Figs. 1 and 2 respectively. The first images, shown in Figs. 1(a) and 2(a), are captured at 0 ms, just before the striker hits the primer. After the striker hits the primer there is a short delay of 0.25 ms before the propellant starts burning. At time 0.3 ms the slider moves forward and the cartridge case becomes partly visible. At this point the maximum temperature on the chamber rises rapidly to 310 K. At time 0.8 ms the slider moves further forward and exposes a good part of the cartridge case inside the chamber. At this point the maximum temperature on the wall of the cartridge cases near the mouth rises to its maximum of 363 and 353 K on aluminium cases and brass cases respectively as seen in Figs. 1(c) and 2(c). Moreover the temperatures on the rim of the cartridge cases are as low as 303 K. The maximum gas temperatures are recorded as 412 K when an aluminium case is used and 373 K for brass. At time 1.2 ms the cartridge case rotates as it leaves the chamber. The gas temperature is measured as 416 K for both the aluminium and brass cases. At this point the whole cartridge case can be seen from which the outside surface temperature profiles are plotted. The temperatures on the surface near the rim are much lower than the temperatures towards the mouth of the cases, as seen in Figs. 1(d) and 2(d). The temperature on the aluminium cartridge case near the mouth is 358 K, whereas on the brass cartridge case is 336 K, a difference of 22 K. Moving along the surface towards the rim of the cases the temperature drops to 293 K. The difference between the temperature near the mouth and near the rim is 65 K for aluminium and 43 K for brass cases. At time 2 ms the cartridge cases rotate further only to expose the high temperature on the base especially evident on and around the primer region. The temperature on the base of the aluminium case is around 372 K which is higher than the rest of the case. The temperature near the cartridge mouth is around 345 K which is lower than 358 K seen at time 1.2 ms. The temperature on the base of the brass cartridge case is around 331 K which is 41 K lower than on the aluminium case. The temperature of the brass cartridge case near the mouth is around 308 K. Again this is lower than the 336 K measured at time 1.2 ms. However near the cartridge rim the temperature remains approximately the same as at earlier times. Figs. 1(e) and 2(e) clearly show that the temperature on the base of the cartridge cases is always higher than on the rest of the cartridge cases at any given time. At time 2.4 ms the temperatures on the base and near the mouth of aluminium case are nearly equal around 358 K. The brass cartridge case shows lower temperatures of around 328 and 308 K on the base and near the mouth respectively.

2.3. Thermocouple measurements

From temperature data the cooling rate of aluminium and brass cases were found to obey the following relationship:

$$T_A = -4.47\ln(t) + 329.6 \quad (1)$$

$$T_B = -5.64\ln(t) + 322.35 \quad (2)$$

T_A and T_B are the temperatures (K) of aluminium and brass cases respectively, and t is the time in seconds. These give estimates of the maximum temperature achieved as 361 K for aluminium and 363 K for brass.

2.4. Micro-hardness evidence

Results given in Table 1 show that material hardness was not affected by the firing.

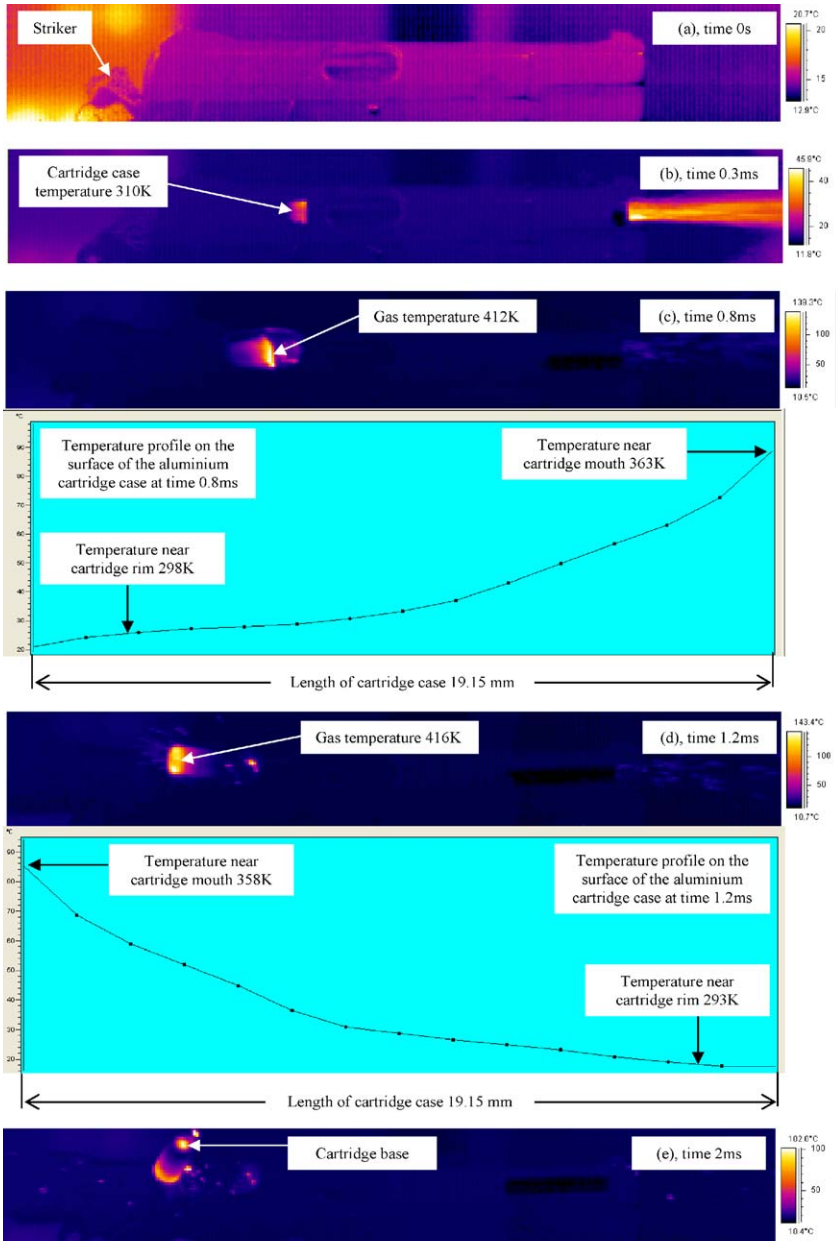

Fig. 1. Infrared images showing the temperature on a 9 mm aluminium cartridge case.

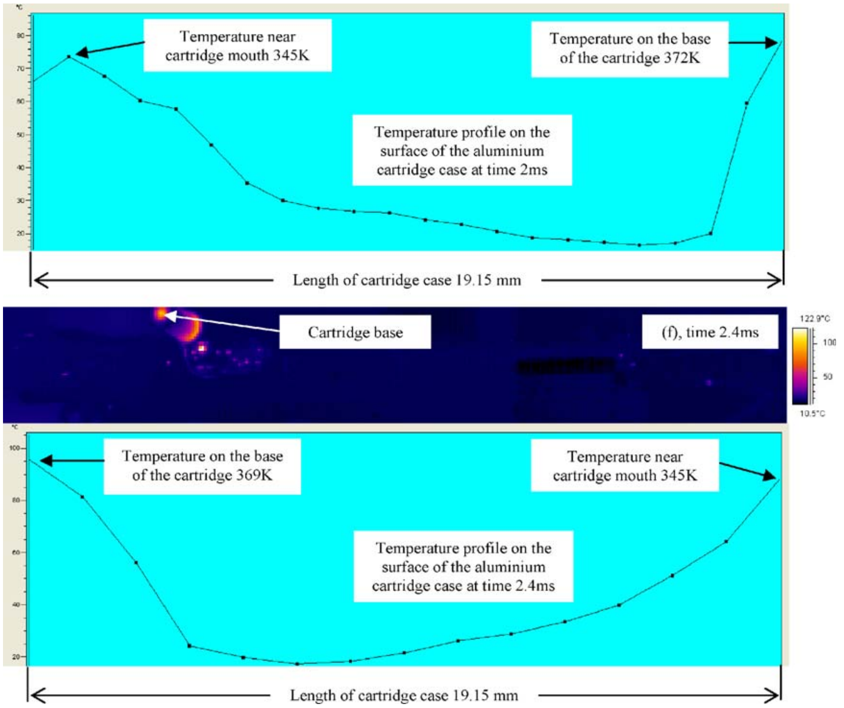

Fig. 1. (*Continued*).

2.5. DNA testing

Results given in Table 2 indicate that DNA can be recovered from cartridge cases that had been knurled and fired.

3. Discussion of results

The results of DNA testing shown in Table 2 indicate that the DNA is capable of surviving the temperature cycle experienced by the external surface of the cartridge case. This could be because a very high temperature was only seen for a period of time measured in milliseconds or that the maximum temperature achieved was much lower and compatible with the reported long term survival of DNA.

Experimental results from the thermal imaging camera shown in Figs. 1 and 2 suggest that maximum temperatures of the external surface are 372 K for an aluminium case and 336 K for a brass case. These temperatures are much lower than even the 573 K estimated at the centre of cortical bone after a vehicle fire by Holden et al. [6] as well as those implied by the ability to use DNA to identify fire victims as noted by Calacal et al. [5]. The significance of the measured temperatures of Figs. 1 and 2 can also be related to thermal cycles seen in the techniques of polymerase chain reaction (PCR) amplification used by forensic scientists. These involve short (up to 60 s) multiple anneals at temperatures of 367–368 K as part of the amplification cycle [1]. The methods used for DNA amplification [11,12] involve the heat treatment sequence of 368 K for 11 min, 28 cycles of 367 K for 1 min, 332 K for 1 min, 345 K for 1 min, 333 K extension for 45 min. This would suggest that the short periods, such as the milliseconds seen in this work (Figs. 1 and 2), at temperatures below 373 K would not damage the ability to use the DNA forensically any more than does the present use of multiple cycles of PCR amplification. This latter process has been reviewed by Gill [13] who has analysed the advantages and limitations of such an amplification process in forensic science.

The results from the thermal imaging (Figs. 1 and 2) suggest that the maximum external temperature of aluminium alloy cartridge cases are higher than the corresponding temperatures of brass cartridge cases. This can be confirmed by the carrying out of unsteady state heat transfer calculations for aluminium, brass and steel. Data for the thermal properties of the materials [14] are given in Table 3. Assuming a semi-infinite medium the temperature at any distance in from the inner surface can be calculated as a function of time for the materials. Results for an inner surface temperature of 915 K are shown in Fig. 3 for a distance of 0.5 mm. The assumption of an inner wall temperature of 915 K is made, rather than the propellant temperature of 2273 K, on the basis that there is no evidence of melting on the inner surface even for an aluminium alloy case. Results show that the temperature reached increases with the increasing material thermal diffusivity seen in Table 3, confirming the experimental results where aluminium alloy cases are seen to be hotter than the corresponding brass cases. Temperatures seen in Fig. 3 are higher than those measured and shown in Figs. 1 and 2, this being essentially due to the fact that the inner surface temperature is actually lower than 915 K. Table 1 shows the absence of any reduction in the hardnesses for both aluminium and brass. This indicates that there has been no softening due to recrystallization of the cold-worked cartridge case material, confirming that the maximum temperature at the inner surface is lower than 915 K. The limiting factor reducing the inner wall temperature is the slow heat transfer across the boundary layer between the burning propellant and the cartridge case.

Consideration of the unsteady state heat transfer suggests that the temperatures of the base of the cartridge case should be lower than that seen along the wall of the case, since the thickness of the case is greater at the base than at the wall. This is not shown experimentally, as seen in Figs. 1 and 2, but can be explained in terms of the longer time that the material of the base is in contact with the hot gases of the burning propellant, remembering that the burning starts at the base via the primer. This would mean that the inner wall temperature at the base of the cartridge case would be at a higher temperature than would be the inner wall temperature of the mouth of the case. This would have a greater positive effect on the temperature of the external surface than the negative effect of the greater thickness of metal.

The estimates obtained from thermocouples measuring the cooling of cartridges after long times do not show the differences

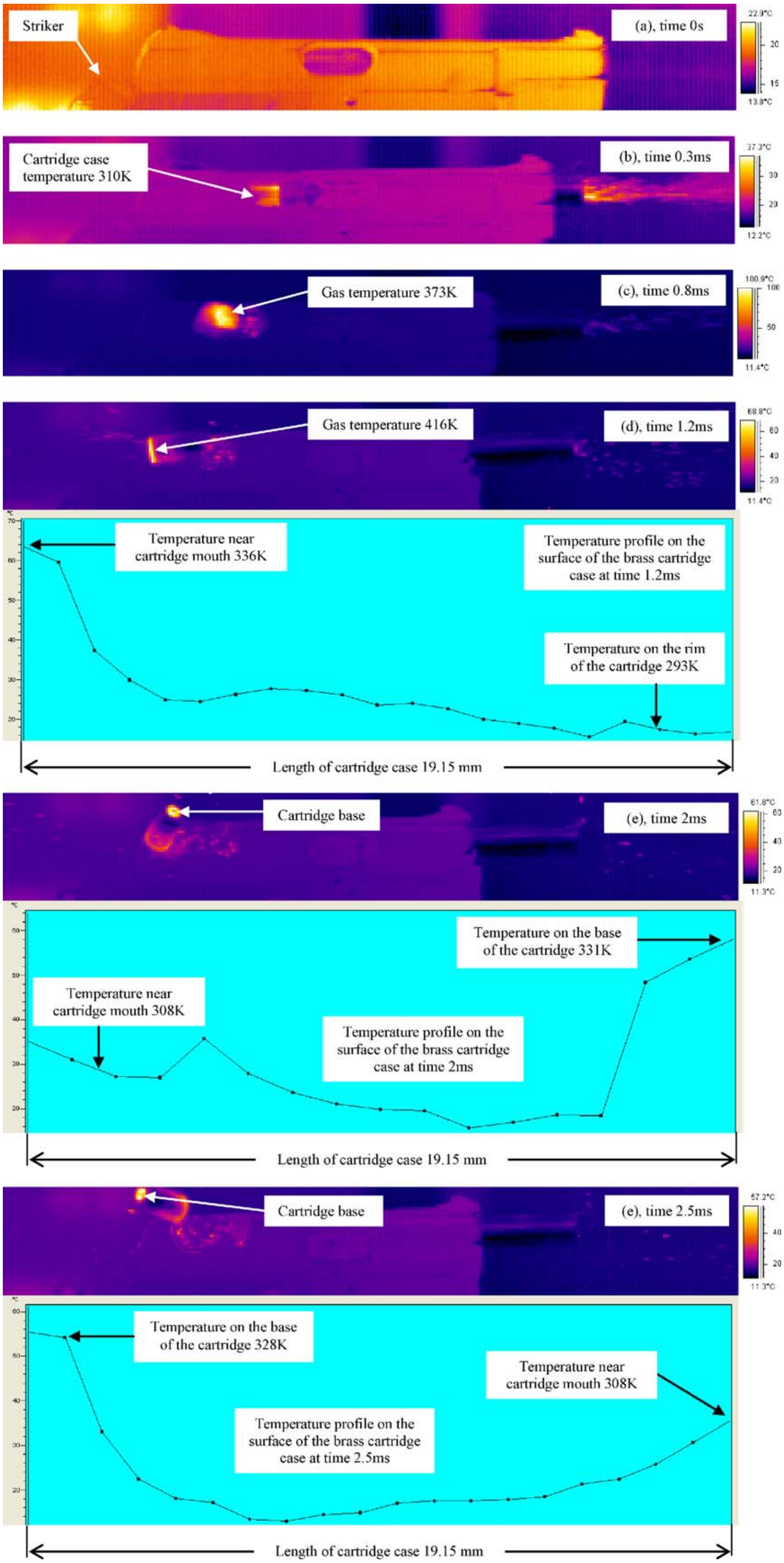

Fig. 2. Infrared images showing the temperature on a 9 mm brass cartridge case.

Table 1
Micro-hardness (100 g load) of inner surface before and after firing.

Brass		Aluminium alloy	
Unfired	Fired	Unfired	Fired
209 ± 11.9 (N = 9)	211 ± 11.3 (N = 9)	154 ± 8.2 (N = 9)	153 ± 8.9 (N = 9)

Table 2
DNA results from cartridge cases that has been knurled and fired.

Sample no.	No. of alleles	Donor matches	Non-donor alleles	% ND alleles	% profile[a]
1	14	11	3	21.4	63.6
2	21	21	0	0.0	95.5
3	18	18	0	0.0	81.8
4	4	4	0	0.0	18.2
5	18	18	0	0.0	81.8
6	8	8	0	0.0	36.4
7	18	17	1	5.6	81.8
8	22	22	0	0.0	100.0
9	20	18	2	10.0	90.9
10	20	19	1	5.0	90.9
Mean	16.3 ± 5.93				

[a] Based on all observed alleles including contaminant peaks.

Table 3
Material properties [14].

Property	Brass C26000	Aluminium 1100-H12	Aluminium 2014-T4	Steel AISI 1012
Density (kg/m^3)	8530	2710	2800	7870
Heat capacity (J/kgK)	375	904	880	472
Thermal conductivity (W/mK)	120	220	134	49.8
Diffusivity (m^2/s)	3.75×10^{-5}	8.98×10^{-5}	5.44×10^{-5}	1.34×10^{-5}
Melting range (K)	1188–1228	915–955	780–911	

between aluminium and brass but do confirm the presence of relatively cool external surfaces on cartridge cases as seen experimentally in Figs. 1 and 2.

All these results indicate that DNA survival is due to the fact that temperatures reached during the firing sequence are relatively low. These are substantially lower than those estimated to have been reached by the bones of fire victims, where identification by DNA has been shown to be possible and comparable to those experienced during standard DNA amplification sequences. Thus the ability to recover DNA from a fired cartridge case is essentially controlled by the surface roughness pattern noted by Xu et al. [4] and appears not to be affected by the short temperature excursion seen by the material of the external surface of the cartridge case.

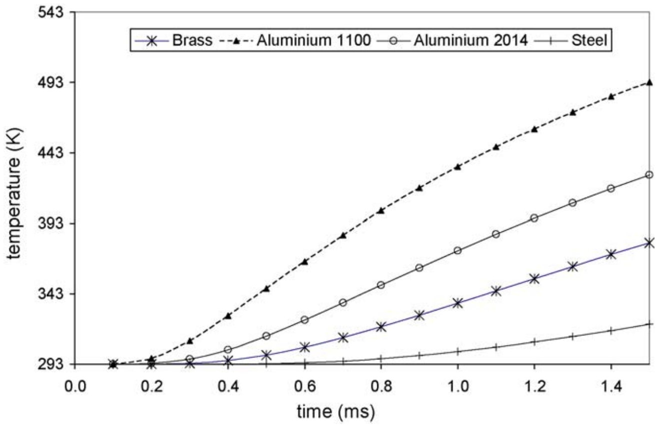

Fig. 3. Calculated temperature on the outer surface of aluminium, brass and steel cartridge cases, assuming inner surface temperature of 915 K and 0.5 mm wall thickness.

4. Conclusions

1. DNA can be recovered from fired cartridge cases.
2. The maximum temperatures achieved especially for brass cartridge cases appear to be below the temperatures seen in PCR amplification processes and substantially below the likely temperatures encountered by the bodies of fire victims. Thus the structure of DNA would not be altered in such a way as to prevent its forensic utility since the times spent at temperature are orders of magnitude shorter than those in PCR amplification processes. This is confirmed by measurement of the DNA taken from fired cartridges.
3. The use of a high frequency infrared thermal camera appears to be the most appropriate method to measure the external temperature of the cartridge cases of small arms. Other measuring methods especially those requiring contact are less appropriate due to the lack of space inside the chamber to the cartridge case, the lack of visibility of the cartridge case and the lack of accessibility to the cartridge case.
4. Infrared temperature results clearly indicate that the heat transfer into the cartridge wall is poor but higher into the base of the cartridge case, especially around the primer area. Heat transfer into and around the base of the case is not only due to the propellant burning but also due to the explosion of the primer.
5. The surface temperature of aluminium cartridge cases is higher than that of brass cartridge cases. This is due to the thermal diffusivity of aluminium being higher than that of brass.
6. Material hardness on the inside surface of the cartridge cases was not affected by the firing. This indicates that the temperatures reached were insufficient for recrystallization to take place.

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