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Cleaning deteriorated elements of ammunition: Development of a procedure applied to cartridge cases from the Second World War

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ABSTRACT

Deteriorated elements of ammunition can be found while investigating different types of events. Exposure to adverse environmental conditions may lead to metal alteration (corrosion) or organic material deposition (contaminations) on the exposed elements of ammunition. From a forensic perspective, both types of deterioration pose challenges when observing marks left by the firearms used to discharge the corresponding ammunition (e.g. firing pin, extractor). The longer the time of exposure to the adverse environmental conditions, the more challenging the observation of such marks. A literature review highlighted three previously published restorative methods used to clean deteriorated elements of ammunition. The aim of this research is to develop a cleaning procedure applicable to cartridge cases exposed to adverse environmental conditions, while avoiding the degradation of marks left by the firearms used to discharge the corresponding ammunition. A first batch of 21 brass cartridge cases dating back to the Second World War (WWII) was used to develop a cleaning sequence involving the three methods. The efficiency of each restorative method was qualitatively assessed using optical macroscopy and the Evofinder® ballistic identification system. The developed sequence relies on successive applications of Tickopur® TR 7 (a diluted soft metal cleaner), sulfuric acid and finally Aqua Regia (HCl 37% and HNO_3 75%), all of them involving ultrasonic baths. The resulting cleaning sequence was subsequently applied to three batches of Second World War cartridge cases discovered in France and Russia. This sequential procedure allows the effective cleaning of WWII brass cartridge cases while highlighting different marks left by firing pins, extractors, ejectors, and breech faces. Applying a forensic analysis and comparison process to the marks highlighted on these elements of ammunition can support the verification of historical facts when reconstructing events which took place more than seventy years ago.

1. Introduction

Different scenarios involving the use of firearms such as genocides, war events or murder cases can lead to a forensic investigation of deteriorated elements of ammunition. These elements of ammunition are likely to be degraded since they have remained in adverse conditions for decades. This exposure to environmental conditions has deteriorated, contaminated or corroded the ammunition components. When studying discharged elements of ammunition degraded by a long-term exposure to adverse conditions (e.g. humidity, heat, frost), effects such as the corrosion of metallic surfaces or the deposition of material will hinder the observation of the different characteristics of marks left by the firearms.

A distinction between two types of deterioration occurring on fired cartridge cases is considered in the context of the present research. On one hand, alteration refers to the metal degradation phenomenon over time, mostly caused by corrosion when the metal is exposed to atmospheric conditions. On the other hand, contamination encompasses all processes of organic material deposition (e.g. soil, plants, limestone) on the cartridge case surface. Despite its crucial influence on further forensic examination in such situations, the cleaning process of alteration and contamination on ammunition has been the subject of a few studies. In an article about the examination of damaged lead or jacketed bullets received by a forensic laboratory, Booker described procedures

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Table 1
Description of the four batches of cartridge cases.

Batch. Location	Calibre	Manufacturer[8]	Specimens	Deterioration
1. Cannes, France	.30–06 Springfield	Des Moines Ordnance Plant, USA (1942)	2	Medium contamination, medium alteration
		Lake City Ammunition Plan, USA (1942)	17	
		Remington Arms Co., USA (1942)	1	
		Saint Louis Ordnance Plant, USA (1942)	1	
2. Tanneron, France	.30–06 Springfield	Frankford Arsenal, USA (1941)	10	High contamination, medium alteration
3. Massif de l'Esterel, France	.45 Automatic	Frankford Arsenal, USA (1941)	6	Low contamination, low alteration
		Union Metallic Cartridge Co., USA (1942)	4	
4. Demyansk, Russia	7,92 × 57 mm Mauser	Deutche Wafen- und Munitionsfabriken, Germany (1937)	1	High contamination, high alteration
		Dynamit Alfred Nobel, Germany (1934)	1	
		Finower Industrie, Germany (1937)	1	
		Hugo Schneider AG (HASAG), Germany (1935 and 1939)	2	
		Metallwerke Wolfenbuttel, Germany (1937)	2	
		Polte Armaturen und Machinenfabrik, Germany (1937 and 1938)	2	
		Presswerk Metgethen, Germany (1936)	1	

to address the contamination problem, including the use of dissolution and ultrasonic techniques [1]. Booker concluded that both the type of deterioration and the bullets' coating influenced the choice of the technique to be used to clean them. Building on Booker's work, Randich and colleagues also studied a range of brass cartridge cases and coated bullets from multiple homicide cases. They obtained positive results by applying Booker's solution. However, depending on the environment in which the elements of ammunition had been located, detailed marks on the elements of ammunition were found to be altered [2]. Larrison studied the marks left on 48 fired bullets and 32 discharged cartridge cases after these elements of ammunition had been exposed to various environmental conditions (i.e. open air, water, soil, animal carcass) over two years [3]. Every six months, specimens were collected, and comparisons were performed after applying a sulfuric acid-based cleaning solution. While efficient to deal with the corrosion of the elements of ammunition, this cleaning solution had to be applied gradually, as its effects could influence the marks used for forensic identification purposes. Corrosion cleaning is also mentioned in literature related to archaeology in the context of military battles, although limited details were provided in terms of methodology [4]. More recently, a comparison of three corrosion cleaning methods on various metallic surfaces has been carried out by Gibson [5]. Around 1300 cartridge cases with different compositions were exposed to six environmental conditions to test three restorative techniques. Cartridge cases were studied monthly, for each of the six environmental set ups. The results of this extensive series of experiments highlighted the potential of the solution proposed by Randich and colleagues, as well as those obtained with a solution called Aqua Regia [5]. Specific studies are also conducted on alteration without taking into account contamination [6]. While interesting in terms of method development, the applicability of such an approach to actual cases remains limited, particularly for old elements of ammunition dating back to the Second World War, as they underwent both alteration and contamination over several decades.

In the context of elements of ammunition dating back to the Second World War, marks on cartridge cases exposed to outdoor conditions for seventy years have been studied when trying to reconstruct an event which occurred in 1944 [7]. The deteriorated cartridge cases were cleaned using Tickopur® TR 7, a universal cleaning solution. Observation with a comparison macroscope revealed class characteristics as well as striae. In such a context, elements of ammunition can be studied to complement or assess information based on testimonies, written documents, or photographs. From a forensic perspective, class characteristics (shared by different firearms) might be sufficient to assist the reconstruction of an event, although restorative methods might highlight detailed striations as well. The latter reference being one of the few examples in which promising results were achieved on elements of ammunition progressively deteriorated over decades under adverse conditions. Marks originally left by firearms do not seem to be affected

Fig. 1. Selection of cartridge cases from Batch 1 (Cannes, France).

by the cleaning process. Despite the results obtained with the methods identified through this literature review, not all of them have been tested on so-called historical elements of ammunition, which constitute the most complex specimens in terms of deterioration. Additionally, the application of these methods in sequence has not been addressed either.

The purpose of the present study is to develop a cleaning methodology for deteriorated elements of ammunition, while ensuring that the marks left on them by firearms could still be exploited in a forensic context. A batch of 21 brass cartridge cases dating back to the Second World War is used to develop a cleaning sequence by cross-referencing the performances of Sulfuric acid, Aqua Regia and Tickopur, three cleaning methods previously described in the literature. Subsequently, the most efficient cleaning sequence is applied to three other sets of fired cartridge cases in order to assess the effects of the sequenced methods on marks originally left by the firearms used to discharge the ammunition.

2. Material and method

2.1. Cartridge cases specimens

Four batches of brass (copper-zinc alloy) cartridge cases were collected through metal detecting surveys on different areas where battles occurred during the Second World War, in the South of France and in Western Russia. Batches of cartridge cases 1–3 were found in a dry environment, typical of the French Côte d'Azur area. They were buried a few centimetres deep in earthy soil with many gravels or lying on the surface. Cartridge cases from Batch 4 were found at a depth of about 1 m in an earthen trench in a very wet area. Table 1 shows the characteristics of each batch as well as a qualitative assessment of the extent of the degradation for each of them. Figs. 1–4 show illustrations of each batch. The exact composition of each cartridge case has not been

Fig. 2. Cartridge cases from Batch 2 (Tanneron, France).

Fig. 3. Cartridge cases from Batch 3 (Massif de l'Esterel, France).

Fig. 4. Cartridge cases from Batch 4 (Demyansk, Russia).

defined (e.g. by means of instrumental analysis). Nevertheless, none of the cartridge cases are ferromagnetic. Additionally, research into specialised literature resources based on the general description, calibre and headstamp of the studied cartridge cases lead to the conclusion that they are made of brass. For Batch 4 specifically, all cartridge cases are stamped " S* ", indicating that they are made from a brass alloy of 72% copper and 28% zinc.[1]

Unlike Batches 2–4, the first one is of lesser historical value since a very large quantity of cartridge cases have been discovered in the same place, with no apparent relation to a historical event of interest. Consequently, cartridge cases from the Batch 1 were selected for the development of the cleaning methodology, while the other batches were used to test the results of the defined cleaning sequence.

2.2. Cleaning methods

Three cleaning methods presented in the literature were tested, their main steps are summarized in Table 2.

Table 2
Main steps of the tested cleaning methods.

Step	Tickopur (Gassend et al. [7])	Sulfuric acid (Randich et al. [2])	Aqua Regia (Crowe and Morgan-Smith [9])
1	Tickopur® TR 7 [5%] *50 °C* *Sonication 15 min*	Light-stabilized TCE *Room Temperature or 75 °C* *Sonication 2 min to 2 h*	Acetone (HPLC grade) *Room Temperature* *Sonication 2 min*
2	mQ water *Room Temperature* *Sonication 2 min*	Acetone *Room Temperature* *Sonication 2 min*	Aqua Regia *Soaked swab or short soak (1–2 s)*
3	Mellerud®	Alkaline solution *pH ≈ 12.5; 50 °C* *Sonication 2 min*	mQ water *3 successive baths* *Room Temperature* *Sonication 2 min*
4	-	Cleaning solution *Room Temperature* *Sonication 2–3 sec to 1 min*	-
5	-	mQ water *2 successive baths, Room T* *Sonication 2 min*	-

[1] http://www.armeetpassion.com/792%20JS.html.

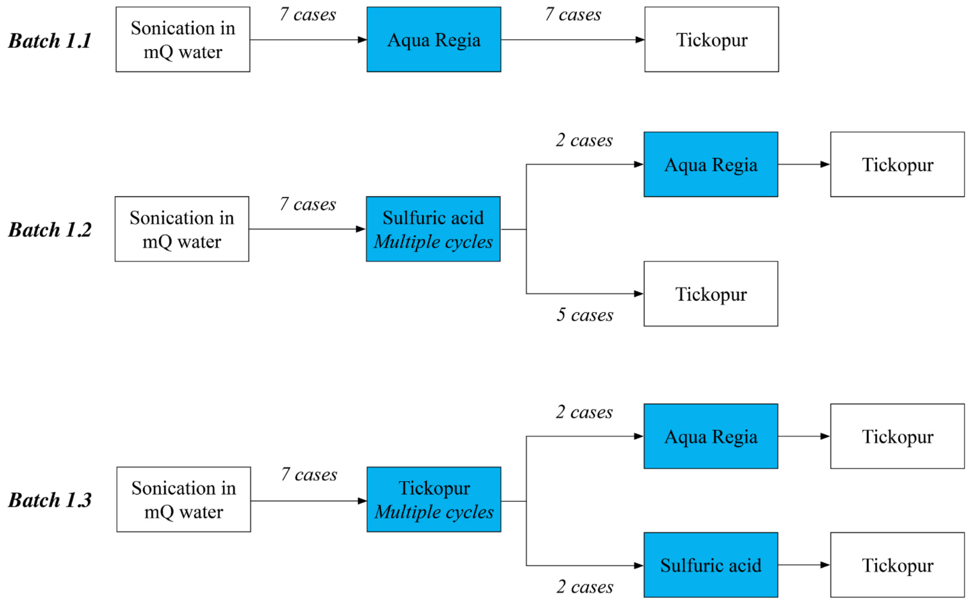

Fig. 5. Tested sequences involving the three selected methods.

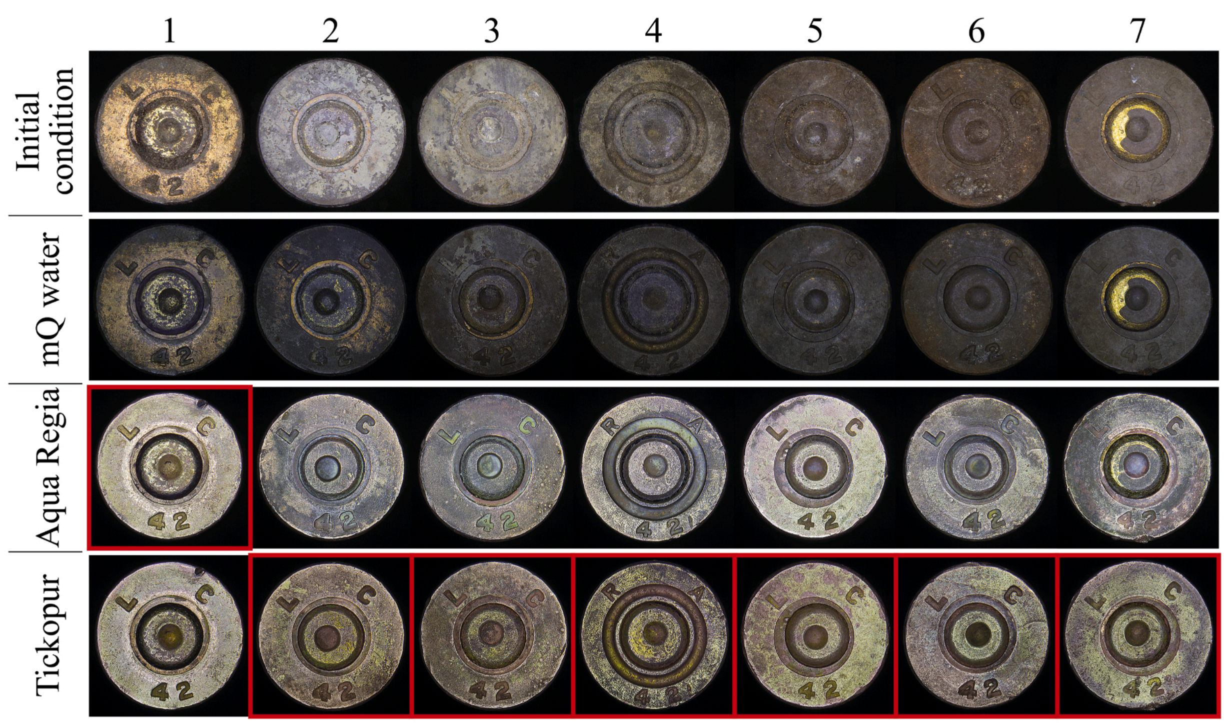

Fig. 6. Evolution of headstamp condition for cartridge cases from Batch 1.1.

Before applying any of them, the cartridge cases are first sonicated in a bath of mQ water at 75 °C for 2 min. Besides, for each of the sonication steps described below, the cartridge cases were placed one by one in separate glass beakers to avoid any contact between them which could create marks during the sonication. The Tickopur method, as described by Gassend et al. [7], was selected due to its previous results for cartridge cases having spent a long period of time in outdoor conditions. The Sulfuric acid method[2] applied by Randich et al. [2] was also included in the experiments, as well as the Aqua Regia[2] since both methods did not differ significantly in terms of results. Initially

[2] As opposed to the Tickopur method, specific precautions should be taken when preparing and storing reagents used for both the Sulfuric acid and the Aqua Regia methods. Specifically, the appropriate protective equipment should be worn, and proper containers should be selected. Finally, steps such as the preparation of the Aqua Regia should be carefully studied, as the adjunction of nitric acid to the hydrochloric acid produces an exothermic reaction.

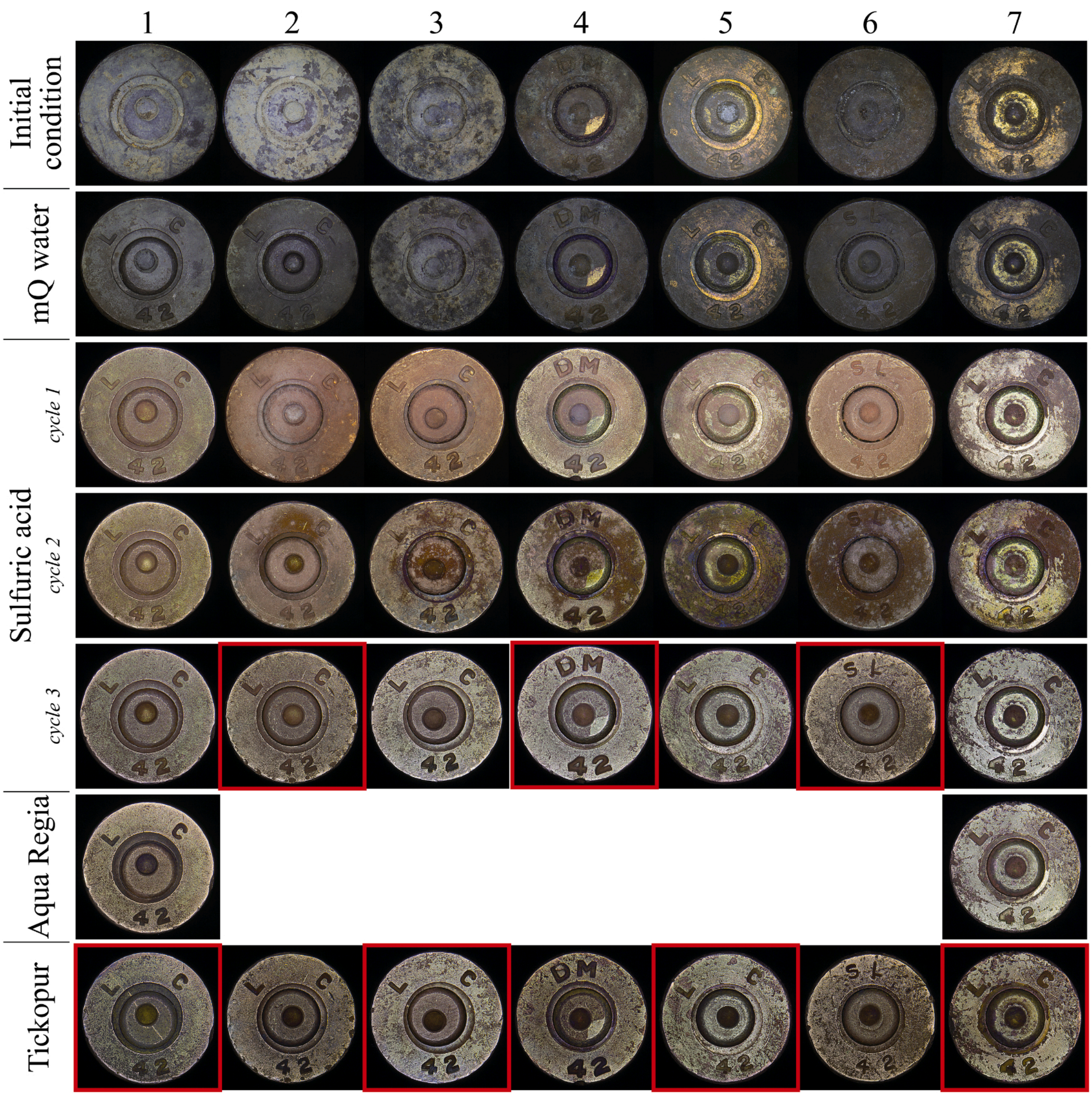

Fig. 7. Evolution of headstamp condition for cartridge cases from Batch 1.2.

introduced by Crowe and Morgan-Smith [9], the Aqua Regia method showed very promising results when applied by Gibson [5].

2.2.1. Tickopur (Gassend et al., 2019)

The Tickopur method consists of a succession of three steps. First, the cartridge cases are sonicated in a bath of 5% diluted Tickopur® TR 7 (Ultraschallbad AG) at 50 °C for 15 min. The specimens are sonicated again for 2 min in mQ water but at room temperature, before being cleaned with Mellerud® (Mellerud Chemie GmBH) a soft metal cleaner used to prevent mould. Gassend et al. mentioned a repetitive application of the entire process three times, while it could technically be applied until there is no more improvement in terms of cleaning [7].

2.2.2. Sulfuric acid (Randich et al., 2000)

The cartridge cases are first sonicated in a bath of light-stabilized anhydrous trichloroethylene (TCE) (Sigma-Aldrich) at reagent grade for two minutes, and at room temperature in the absence of organic debris. In case organic debris are present, the sonication should be at 75 °C and ranging from 2 min to 2 h. Then, the cartridge cases are sonicated for 2 min in HPLC-grade acetone (Sigma-Aldrich) at room temperature. The alkaline solution used for the next sonication step (2 min at 50 °C) is composed of an aqueous mixture of 10% (by weight) of sodium metasilicate (Na_2SiO_3) and 10% of ethylene glycol monobutyl ether ($C_4H_9OCH_2CH_2OH$) at pH ≈ 12.5 (both from Sigma-Aldrich). This is followed by a sonication at room temperature in a cleaning solution of 3% concentrated sulfuric acid (H_2SO_4), 5% thiourea (CH_4N_2S) and 0.1% sodium lauryl sulfate solution ($CH_3(CH_2)_{11}OSO_3Na$) at room temperature (all three from Sigma-Aldrich). The cartridge cases are sonicated for 2–3 s for specimens with a light deterioration, and up to one minute if they present a high level of deterioration. The application of the cleaning solution followed by the sonication can be repeated as many times as necessary.

2.2.3. Aqua Regia (Crowe and Morgan-Smith, 2005)

The cartridge cases are sonicated in a first bath of HPLC-grade acetone from Sigma-Aldrich at room temperature for 2 min. The Aqua Regia consists of a 3:1 mixture of 37% ACS reagent grade hydrochloric acid (HCl) and 70% nitric acid (HNO_3) purified by redistillation (≥ 99.999%) (both from Sigma-Aldrich). It is applied on the cartridge cases either with a soaked swab or by short soak (1–2 s). Then, the specimens should be rinsed and sonicated in three successive baths of mQ water for 2 min at room temperature.

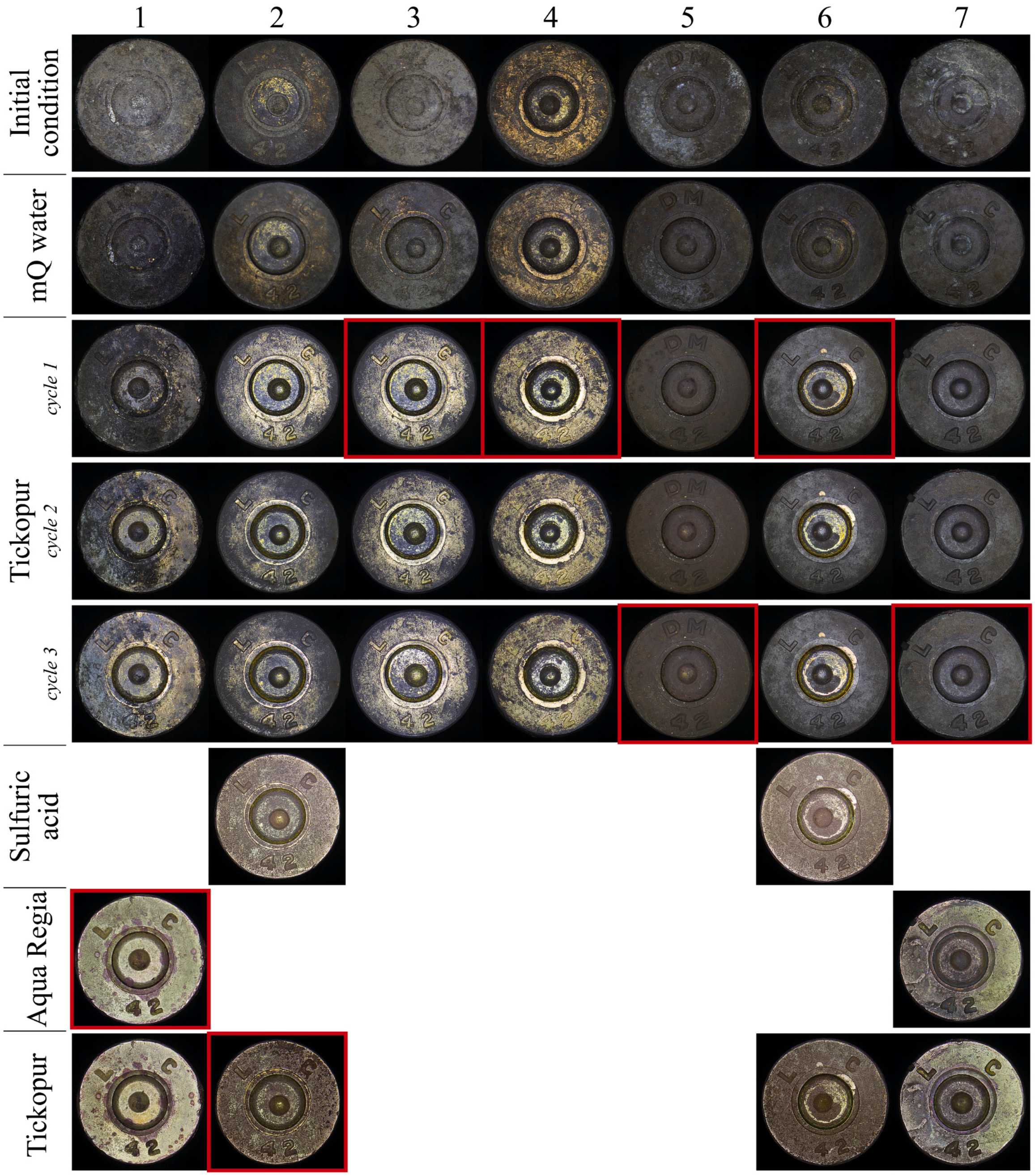

Fig. 8. Evolution of headstamp condition for cartridge cases from Batch 1.3.

2.3. *Effectiveness of the cleaning methods and combination in a sequence*

The tests were carried out on the cartridge cases of Batch 1 (Cannes). The 21 brass cartridge cases were separated into three sub-batches (1.1–1.3) of seven specimens equivalent in terms of degradation and composition, then each specimen was numbered to observe the effects of one of the three cleaning methods.

The methods were put in sequence considering their respective aggressivity for the surface of the cartridge cases (Fig. 5). The condition of the cartridge head after the application of each method was qualitatively assessed and documented to evaluate the contribution of this step. The assessment relied essentially on the overall improvement of the surface details and the firing pin marks of the cartridge head. Both the intrinsic and extrinsic characteristics of the studied cartridge cases were observed and documented with a Leica FS C comparison macroscope (Leica Microsystems). In all scenarios (Figs. 6–8), the best result is identified with a red frame. The quality of the improvement after the application of each cleaning method was only assessed by a visual – hence subjective – examination. Images of the head of the cartridge cases were also acquired using the ScannBI Technology Evofinder® system (version 6.4.0.152).

Aqua Regia (very aggressive due to the use of hydrochloric acid) was tested by itself, while another sequence started with multiple cycles of the Sulfuric acid method. Two cartridge cases from this batch were selected to test the subsequent application of the Aqua Regia solution. The longest sequence started with multiple cycles of Tickopur. Following these cycles, the Sulfuric acid solution was applied to two cartridge cases while two others were treated with Aqua Regia. As illustrated in Fig. 5, each series of tests started with a sonication step in mQ water and ended with a Tickopur cycle to avoid a subsequent degradation of the specimens.

The experiments led to the definition of an optimised sequence of

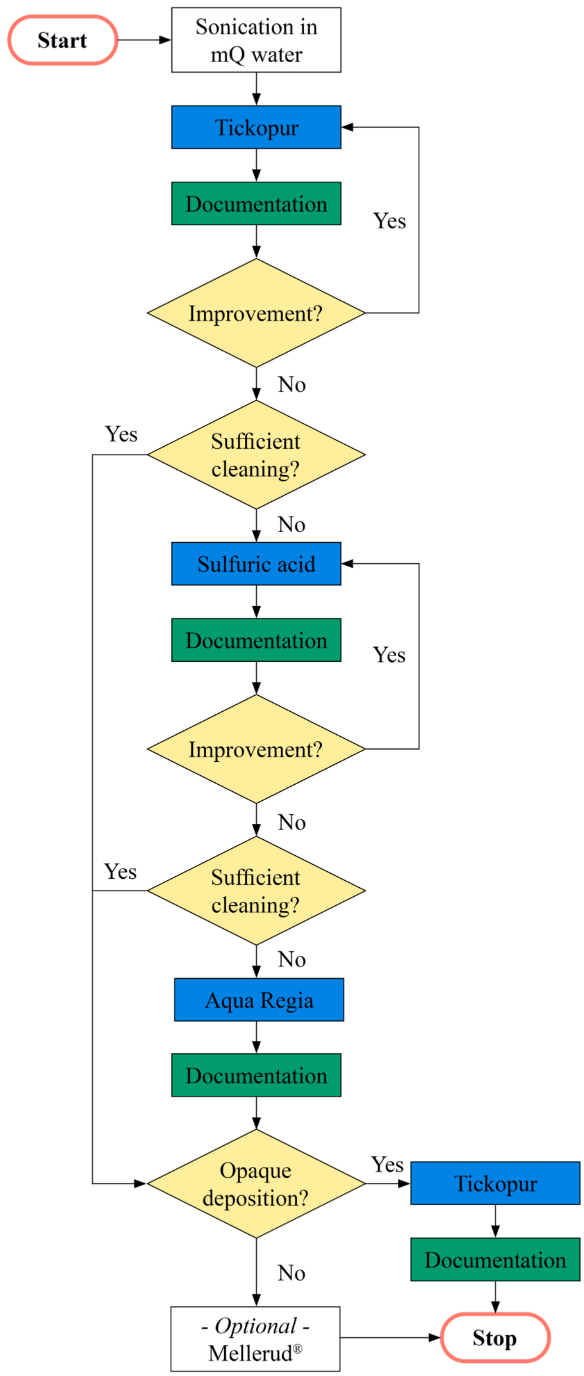

Fig. 9. Cleaning method in sequence based on the results obtained with the three tested methods.

cleaning methods. The newly defined sequence was applied to the cartridge cases of Batches 2–4, leading to a few adjustments in the general cleaning method.

3. Results and discussion

3.1. Tested methods and sequence definition

3.1.1. Results for Batch 1.1

As illustrated in Fig. 6., the Aqua Regia solution offers good results in terms of restoration for all cartridge cases. However, for both the firing pin and breech face marks for example, the Aqua Regia application causes the deterioration of detailed characteristics. A thin opaque deposition is also observed on the entire cartridge head surface after using this method. In most cases, a subsequent application of the Tickopur method helps address this issue, as illustrated with cartridge cases 2–7 in Fig. 6.

3.1.2. Results for Batch 1.2

Consecutive cycles of the Sulfuric acid method appear efficient to clean deteriorated specimens and highlight characteristics of marks left by the breech face. A significant improvement is noted regarding the quality of these marks (Fig. 7), although such an improvement does not apply to firing pin marks for which the fine characteristics are deteriorated. The current set of experiments led to the conclusion that the best option is to start with a 20 s sonication cycle (at the maximum) and adapt according to the results. Less deteriorated cartridge cases require a shorter time of sonication, as opposed to heavily deteriorated cases. A further application of the Tickopur method turns out to be successful for two cartridge cases (Fig. 7, cases 2 and 5) out of 5. Positive results are also achieved for the two cartridge cases selected for the subsequent application of the Aqua Regia solution (Fig. 7, cases 1 and 7), even if a Tickopur® TR 7 application is still recommended to avoid the opaque deposition and stabilise the specimen.

3.1.3. Results for Batch 1.3

Applying the Tickopur method leads to a global improvement of the visibility of surface details and marks' quality (Fig. 8). Further iterations of the entire process do not have a deterrent effect on the marks, as described by Gassend et al. [7]. However, the overall benefits in terms of cleaning appear as limited. Subsequent applications of Aqua Regia (cartridge cases 1 and 7) or Sulfuric acid (cartridge cases 2 and 6) do not necessarily improve the results obtained with the first iterations of Tickopur (Fig. 8, see the examples of cartridge cases 6 and 7).

The above-mentioned results led to the definition of the sequence illustrated on Fig. 9. The aggressivity of each method for the cleaned surface and the results obtained for Batch 1 of the cartridge cases were considered to develop a cleaning sequence. Tickopur not being an aggressive method, it can be applied as a first method. The good results obtained with the experiments and the fact that no deterrent effect would appear with more cycles make Tickopur the best choice for a first method. Then, since Sulfuric acid is a rather aggressive method, it should be applied after the Tickopur method especially considering its good results in terms of cleaning and its limited impact on some marks such as the detailed ones produced by the firing pin. Aqua Regia, the most aggressive of the three tested methods, can be applied after the Sulfuric acid method due to its good results for cleaning, despite its limited contribution in terms of quality of marks left by the firearm used to discharge the ammunition. Ending the sequence with another Tickopur application is recommended to remove the potential opaque deposition generated by the Aqua Regia solution. Without such a deposition, the application of Mellerud® only (i.e. the last step of the Tickopur method) to clean and stabilise the surface is also an option.

3.2. Application to cartridge cases

3.2.1. Cartridge cases from Tanneron, France (Batch 2)

Ten brass cartridge cases from Tanneron, France, initially showed a high level of contamination. As illustrated in Fig. 10, multiple cycles of Tickopur were first applied to this set of cartridge cases according to the original procedure (i.e., cycles 1–3). Given the absence of results, two more iterations of the Tickopur method were applied, this time at a temperature of 80 °C, instead of the usual 50 °C (i.e., cycles 4 and 5).

Following the developed sequence, the Sulfuric acid method was then applied to the entire batch, leading to good cleaning of the specimens, and highlighting a set of characteristics on the cartridges' heads. Subsequently, the Aqua Regia solution was applied to the entire batch, as well as a final iteration of Tickopur, although the best results were achieved with the first iteration of Sulfuric acid.

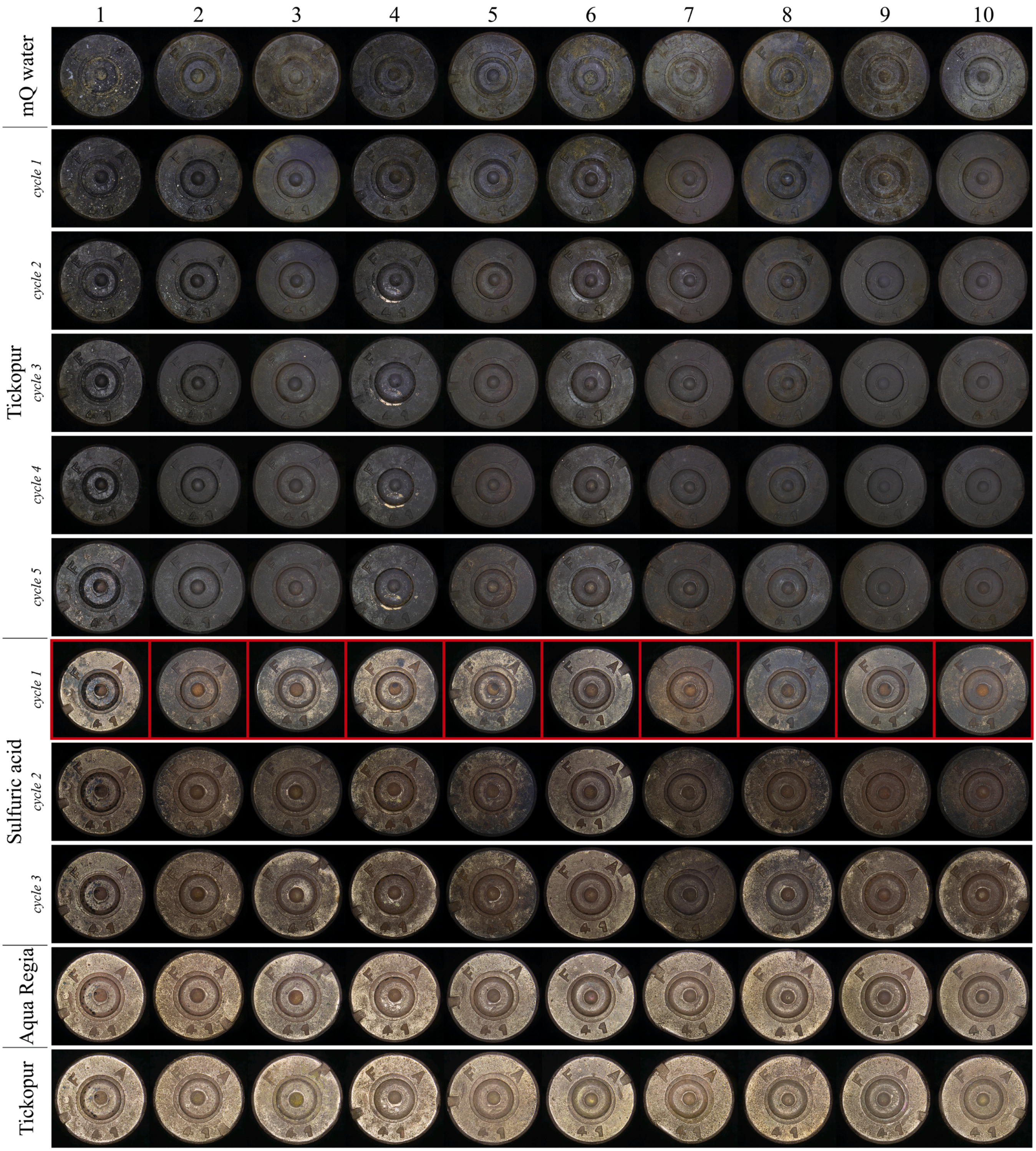

Fig. 10. Evolution of headstamp condition for cartridge cases from Tanneron, France (Batch 2).

3.2.2. *Cartridge cases from Massif de l'Esterel, France (Batch 3)*

The level of both contamination and alteration for this batch of brass cartridge cases was rather low. After three iterations of the Tickopur method, the level of improvement for each cartridge case was limited (Fig. 11). Three cycles of sulfuric acid were then applied to the entire batch, leading to interesting results in terms of cleaning. However, all cartridge cases but one showed signs of mark degradation. Consequently, the Aqua Regia solution was applied on a single cartridge case (without continuing with the Tickopur method since there was no opaque deposition).

3.2.3. *Cartridge cases from Demyansk, Russia (Batch 4)*

When applying the cleaning sequence, a significant improvement was noted for a small number of cartridge cases (Fig. 12, cartridge cases 1 and 2). The limited results obtained with the initial Tickopur application might be explained by the relatively high level of degradation (both contamination and alteration) on all the cartridge cases of Batch 4. A further application of the Sulfuric acid method led to interesting

Fig. 11. Evolution of headstamp condition for cartridge cases from Massif de l'Esterel, France (Batch 3).

results for four cartridge cases, for which the best results were achieved after applying four cycles of this method. The Aqua Regia solution was used for the remaining six cartridge cases, producing the best results of the entire sequence for all of them. The final Tickopur method step was not undertaken due to the absence of opaque deposition.

3.3. *Sequence optimisation and perspectives for comparison*

Given the variety of environmental conditions to which historical elements of ammunition might have been exposed, the behaviour of their surface necessarily remains unpredictable when applying cleaning solutions. Due to this, the assessment of the potential deterioration parameters will remain a qualitative exercise. It is important to consider all applicable options when using a method, with the aim to factor all the parameters including the level of persistence of the degradation (e.g. by applying multiple cycles of a given method or increasing from 50° to 80°C for Tickopur as suggested in the instructions for this method). At best, the application of another cleaning method will not improve the quality of the surface nor have a deterrent effect on the marks left by the firearm used to discharge the ammunition. However, some degradation in terms of fine marks' characteristics has been observed with the most aggressive methods used in the present research. Thus, it is recommended to document all the areas of interest on each cartridge case (including photographs or scans with an automated system) before proceeding with the application of a more aggressive cleaning method. It is important to highlight that the different cleaning solutions were only tested and applied to brass (copper-zinc alloy) cartridge cases in the present research. Indeed, the studied specimen are only Second World War cartridge cases of American and German manufacture, collected in four different locations and having their own environmental conditions. The cleaning sequence may need to be adapted depending on the composition and coating (plating, electrodeposition, or galvanisation) of the cartridge case, or even the environmental conditions, i.e. the alteration (corrosion) or organic material deposition (contaminations) on other locations. Materials (metal or alloy) from other eras and armies may be different and therefore require other appropriate cleaning procedures. This may be the case for steel, which was also used for cartridge cases in the Second World War and later conflicts. If the cartridge case is made of aluminium, copper, or steel with a copper coating, as these metals are much more sensitive and oxidisable, highly acidic and aggressive cleaning methods such as Sulfuric acid or Aqua Regia should be diluted or avoided. The soaking time can also be shortened. Nevertheless, a brief exposure to an aggressive cleaning method (e.g., Aqua Regia) on different metals or alloys than those used in the current study might result in a different reaction. Thus, if a developed method or sequence is to be used to clean a cartridge case, it will be very important

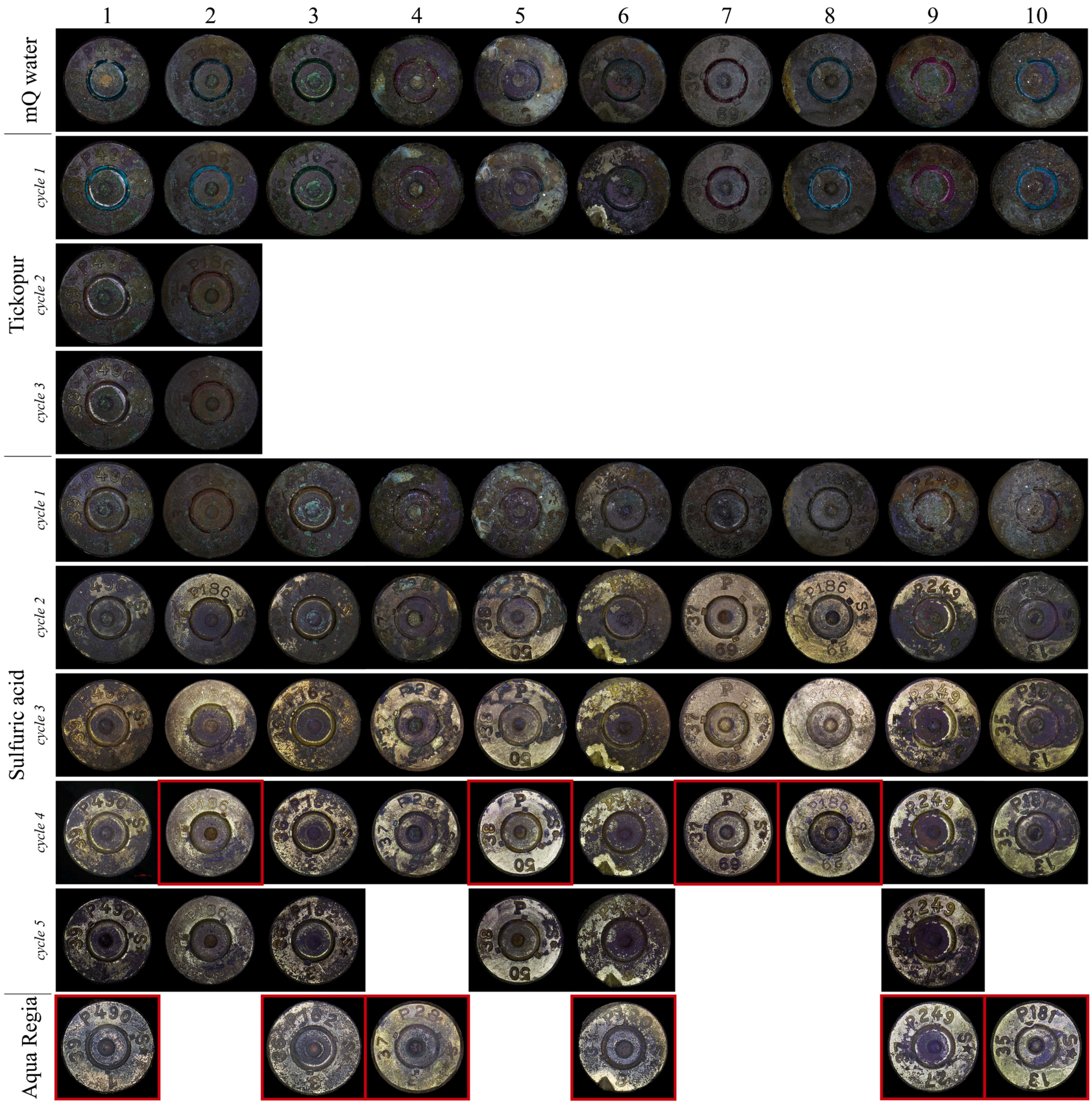

Fig. 12. Evolution of headstamp condition for cartridge cases from Demyansk, Russia (Batch 4).

to consider its composition and the environmental conditions in the area where it was collected. In any case, tests should be carried out beforehand to avoid a permanent loss of historically or forensically relevant information.

The cleaning methods or sequence turned out to be efficient to highlight marks on the brass cartridge cases which could be analysed to highlight some of the characteristics of the firearms used to discharge the ammunition. These marks, and their analysis following a forensic methodology, could be of interest, particularly for cartridge cases from Batches 2, 3 and 4, since they have a significant historical value compared to those from Batch 1. This could support the reconstruction of events that occurred in the regions where the cartridge cases were found or the verification of facts described in different sources of information (e.g. photographs, testimonies, military documents). For example, if a document describes the location of specific troops, analysing the marks related to class characteristics of the firearms used could help confirm how the events occurred. This would imply that there is sufficient knowledge on the firearms used by these troops, as well as their class characteristics (e.g. calibre, type of firearm, brand, model), which is likely to be documented in references about historical weapons. Hypotheses could be formulated in each situation. If the cleaned cartridge cases still show marks left by the firearms used to discharge them, the analysis of these marks could lead to results supporting either the hypothesis that the fired cartridge cases were discharged by the same brand or model of firearms, or the hypothesis that they were fired by firearms from different brands or model. Among the marks that could be used to address such questions are breech face (Fig. 13) and both ejector and firing pin marks (Fig. 14) as observed on

Fig. 13. Example of breech face mark on cartridge case 3 (Batch 1.2).

Fig. 14. Example of ejector and firing pin marks on cartridge case 6 (Batch 2).

cartridge cases from Batches 1.2 and 2 respectively.

Similarly, detailed characteristics on the headstamp of cleaned cartridge cases such as fine striations within specific marks (e.g., firing pin, ejector, or breech face marks) could be analysed, and compared to similar marks on several cartridge cases, the result of which could either support the hypothesis that they were fired by the same firearm, or the hypothesis that they were fired by different ones. Figs. 13 and 14 show examples of striation observed inside firing pin and ejector marks that could be used for comparison purposes.

4. Conclusion

A selection of brass cartridge cases dating back to the Second World War has been used to test the application of three cleaning methods aimed at removing both alteration and contamination, respectively metal corrosion, and deposition of organic material on the outer surface of the cartridge cases. This finding led to the setting up of a cleaning sequence to preserve as much as possible the typical marks left by the discharged firearm on the headstamp of the cartridge cases. Thus, the present research highlights the potential application for the cleaning of cartridge cases exposed to adverse environmental conditions for several decades. Provided that the cleaned elements of ammunition still show marks that could be studied with a forensic methodology (e.g. marks informing on class characteristics or fine striated areas), this could help reconstruct historical events by cross-referencing the findings with non-forensic information, testimonies, or documents describing the event.

By extension, the defined sequence could also be used for forensic casework involving deteriorated elements of ammunition (e.g. cartridge cases left outside for a long time, buried in soil, or exposed to a high degree of humidity) while taking into account their composition and the environmental conditions in the area where they were collected. In this context, the analysis of the marks left by the firearms used to discharge the ammunition is particularly important. After each step, a thorough documentation of the marks, including macroscopic observations, notes, sketches, photographs, or scans using an automated ballistic identification system, is essential before moving forward with further cleaning. Furthermore, a transparent communication with the authority in charge of the investigation (i.e. prosecutor) is essential to manage the expectations related to the cleaning methodology and explain its potential limitations on the evaluation of the forensic results in the context of the case.

CRediT authorship contribution statement

David Rumo: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Denis Werner:** Conceptualization, Methodology, Formal analysis, Validation, Investigation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration. **Damien Rhumorbarbe:** Conceptualization, Methodology, Formal analysis, Validation, Investigation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration. **Géraldine Gobat:** Conceptualization, Methodology, Formal analysis, Validation, Investigation, Writing – review & editing, Visualization, Supervision. **Alain Gallusser:** Conceptualization, Methodology, Validation, Investigation, Writing – review & editing, Supervision. **Jean-Loup Gassend:** Conceptualization, Methodology, Validation, Investigation, Writing – review & editing, Supervision. **Olivier Delémont:** Conceptualization, Methodology, Formal analysis, Validation, Investigation, Writing – original draft, Writing – review & editing, Supervision, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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