Armed conflict impacts on the microscale

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Abstract. Armed conflict has left noticeable marks on our heritage, and has increasingly become a target in itself despite protective legislature such as the 1950 The Hague convention. Both built heritage and stone objects are partially destroyed through the impact of projectiles such as bullets and shrapnel. This study investigates alterations to the fabric of sandstone, a commonly used material for building and sculptures, upon impact using a combination of microscopy and SEM-EDX.

1. Introduction

Although by no means a new phenomenon, incidents of deliberate targeting of heritage during conflict have increased in frequency over the past three years, coinciding with the rise of IS / Daesh. Deliberate destruction of stone icons during the War of the Three Kingdoms (1640s), the destruction of Old Jerusalem (1948) and the Buddhas of Bamiyan (2001) are but a few examples of the scars left by ideologically-driven conflict on our heritage. What is of increasing concern is the advances over the past 50 years in the strength of both the weaponry and the ammunition [1] which has led to an ever-growing array of assault rifles and automatic guns weapons that can create substantial damage to any heritage unfortunate enough to be caught in cross-fire. While little can be done by the material science community to prevent the use of such weaponry, we can ‘prepare for peace’ by investigating the damage likely to occur to heritage and its implications for restoration post-conflict.

Of even greater concern is the very limited availability of any scientific knowledge that could aid in facilitating an understanding of the long-term consequences of these impacts on heritage conservation, and development of strategies needed to salvage conserve damaged heritage where possible. Where materials such as sand and metals have been investigated successfully [2,3], few attempts have been made to map the impact of ballistics into commonly used building materials such as the sandstone examined in this study. In particular, establishing the damage mechanisms behind a bullet impact is keystone knowledge in determining immediate triage as well as long-term conservation strategies [4]; using high-resolution methods such as Scanning Electron Microscopy (SEM) and optical microscopy this study investigates the physical effects of bullet impacts on sandstone surfaces and subsurface matrix. While the study presented here is limited to relatively small (.22 calibre lead bullet) ammunition, the measurements show that damage to the stone structure altered responses to moisture and temperature fluctuations.

2. Methodology

2.1 Materials used

The sandstone used in this study was quarried in the Huesca region in northeast Spain. This type of sandstone is well-consolidated mesoporous sandstone, (average pore size between 40 and 70µm; water absorption capacity of 1.8%). Test blocks measured 15 x 15 x 7.5 cm, with the larger 15 x 15cm surface used as the target. This lithology is particularly suitable for impact testing due to the homogenous matrix, which minimises the potential for test anomalies caused by variations in the sandstone. The samples were shot with .22 calibre lead bullets from a distance of 200m (figure 1). Six sandstone samples were impacted and two were used as control samples.
2.2 SEM/EDX and Optical Microscopy

SEM analysis was carried out to investigate lead deposition using an ESEM FEG. The SEM analysis was completed using a FEI Philips XL30 Environmental Scanning Electron Microscope Field Emission Gun (ESEM FEG) equipped with OSIRIS/ISIS data analysis software. Thin section imaging was undertaken with a Nikon Optiphot-pol microscope (with transmitted and incident halogen light illumination). The following objectives were used for transmitted light observations: x4/0.1 160/-; x10/0.25 160/-; x40/0.65 160/0.17. M-plan Differential Interference Contrast objectives were used for incident light observations: x5 0.1 210/0; x10/0.25 210/0; x40 0.65 210. To produce the images we used a Q-imaging (QICAM fast 1394) high performance IEEE FireWire 12-bit digital CCD (1392 x 1040, 1.4 million pixels, with a pixel size of 4.65µm x 4.65µm) camera system attached by a ½" C-mount. Live image capturing and processing was achieved using Syncroscopy's AcQuis (v. 4.0.1.8) software.

![Figure 1: Optical images of a sample with .22 calibre lead bullet impacts](image)

3. Results and discussion

3.1 Damage mapping

SEM-EDX analysis of the impact area showed noticeable deformation of the subsurface matrix of the sandstone, as well as loss of material from the surface. As figure 2[A] illustrates, the sandstone surface was disrupted and a friable indentation is left within the direct impact site. While the surface loss appeared to be minimal at first visual inspection (figure 1), the SEM-EDX analysis at 500µm scale showed that the material removal area extends sufficiently deep into the sub-surface to create a crater-like indentation. Further exacerbation of this damage is seen in figure 2[B]; compression of the subsurface at the point of impact in the sub-surface zone is resultant in a complex fracture network. The fracture network running parallel to the surface indicate an initial compression at the time of impact, followed by a release of compressive stress and the creation of parallel V-shaped fractures. The combination of this damage indicates that two damage mechanisms in bone which are differentiated in medical studies (crushing and stretching [5]) are simultaneously observed in sandstone impact sites, in the form of a friable surface within the direct impact zone (crushing) and the fracture network surrounding the impact zone (stretching).

The damage to the stone matrix is not limited to the larger stone structure; at still greater magnification, the damage to individual quartz grains is apparent both in the density of the fracturing within the grain, but also the shape of the selective removal of the quartz material. Figure 2[C] shows a quartz grain adjacent to the impact site which has been deformed into a crate-like formation, and is substantially fractured throughout. The surface of grain, when seen under higher magnification (figure 2[D]) appears to have been strained during compression to form plate structures parallel to the surface which are dislodged during the stress-release stage post impact. These two stages, compression and stress-release, mirror those observed at stone structure scale and show that bullet impacts result in the formation of a complex fracture network not only around the surface of the impact zone (as shown in figure 1) but also deeper within the subsurface.
3.2 Ingress of lead into matrix

The final noticeable difference post-impact is the deposition of metals (lead) on and within the surface. The bullet used were strong enough to damage the surface but weak enough to deform and/or melt upon impact, leaving behind a thin film of lead in some areas. Figure 3 shows an overview of the impact area of sample 7 where clear lead residues were observed on the surface. These residues become more obvious when using plane polarised light (see figure 3[B]); the black areas indicate lead deposits. The lead has not only deposited on the surface (as shown on the right hand side of figure 3[B]) but also within the grains (middle and left). Figure 3[C] shows an enlargement of the middle section of 3[B] where the lead intrusion has propagated along a pre-existing fracture within in agrain and has fractured the grain, intruding not only through the centre but also into crevices extending from the centre fracture.

Further examination of the lead intrusion with SEM-EDX showed that the lead forms a thin film over the freshly exposed quartz grain surfaces on the impact site, as illustrated by figures 4[A] and 4[B]. This lead residue, identified using OSIRIS/ISIS software, could potentially affect the chemical and physical properties of the surface post-impact, and needs to be considered when considering options for long-term conservation or restoration of materials affected by bullet impacts.

Figure 3: [A] Photomicrograph in crossed-polars of an impact area showing the general setting of the lead-impacted minerals [B] Plane polarised image of the impact area of sample 7, showing lead intrusions into the surface (circled) [C] Close up of the centre section of the lead intrusions into the surface
4. Conclusions

Though the study is focussed on a relatively small calibre bullet (.22), SEM and OM techniques have clearly demonstrated that bullet impacts on sandstone result in damage to the material at the macro- and micro-scales. This damage comprises material loss from the surface and the formation of a macro-scale fracture network in the subsurface. At the microscale, individual quartz grains are shown to have deformed and have lost material, presumably during stress release. Furthermore, this study has shown that lead form the bullet can penetrate and remain within the subsurface matrix and can even intrude and exploit pre-existing fractures in individual quartz grains. The combination of OM and SEM techniques is therefore a powerful tool for shedding new light on the impact of ballistics on stone surfaces, and could be considered a new and valuable approach to understanding the effects of conflict on built heritage. As shown in this study, impact damage reaches further into the subsurface than initially assumed with visual inspection, and therefore urgent work is needed to understand the impact of a wider array of weaponry ballistics on stone surfaces.

Acknowledgements

The author wishes to express her gratitude to Mr Owen Green for his valuable help and insights in optical microscopy and his assistance with the production of the thin sections. She also thanks the Herefordshire Breech-Loading Rifle Association for their assistance with the sample creations, and Dr Shaun Lavis for his helpful comments. Finally, she would like to thank Prof Heather Viles for the use of materials and equipment in the Oxford Rock Breakdown Laboratory.

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