Hearts and homes: the potential of conservation laser cleaning for post-disaster wellbeing and waste reduction

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Abstract

This paper explores the potential for conservators to use their unique combination of materials and heritage experience to tackle the challenges of recovery in fire affected areas, helping to minimise the waste and greenhouse emissions associated with traditional processes of post-disaster building remediation by facilitating cleaning and repair rather than replacement and disposal of fire affected materials. The focus is not on saving "special" items, but on remediating the broader fabric of homes and possessions that embody a sense of place and identity that sustains wellbeing and aids recovery after disaster. The samples used are painted plasterboard affected by smoke from the 2019 bushfires on the south-eastern coast of Australia. The method being trialled is the use of lasers to remove ash (soot) deposited by the smoke to achieve a reduction in visual reminders of the fire and a surface that is ready for processes such as sanding, plastering or repainting to prepare a home for quick post-disaster re-occupation.

Lasers have been extensively used for cleaning buildings. They use light energy to clean, so do not require abrasives or other chemicals, or touching of the surface. Nanosecond and femtosecond pulse lasers are trialled and the effectiveness of the laser cleaning is analysed using visual assessment, optical microscopy, spectrophotometry and Fourier-transform infrared spectroscopy (FTIR).

Keywords: laser cleaning, personal heritage, restoration, disaster recovery, building decontamination, waste reduction, wellbeing

Introduction

The importance of a circular economy

The recent severe fires that have ravaged many areas of the world have raised concerns that fire conditions will become more and more common with a warming climate, and that the time between wildfire events will shorten. A staggering 21% of Australia's forested areas burned during the 2019/2020 bushfires (Boer et al., 2020), leading to devastation of flora and fauna and destruction of the property and heritage of affected people and communities.

The bushfires also surfaced problems in commercially driven practices of clean-up and damage remediation. The traditional, linear economic model of remediation is predicated on a take-make-consume-dispose pattern of consumption, which is dependent on the availability of large quantities of cheap, easily accessible materials and energy. Furthermore, planned obsolescence is a part of the model, whereby products and materials are designed to have a limited lifespan and require regular replacement. Materials sent to landfill are not accounted for, and there is no motivation to retain materials, to reuse materials, or to recycle materials (Ghisellini et al, 2018). In the aftermath of fires, the influence of the traditional economic model has been clear, as the current remediation pathway, from insurance assessment and pay-out, to builder quotation, material purchase and project management, has been driven by assumptions that damaged materials should be replaced rather than repaired or restored. This model creates a slow process that requires liaison with a complex range of insurance and building contractors (Harms et al 2021); a massive burden of waste (Denhart 2010); and emotional alienation, as the remains of people's personal heritage are recategorised as waste and carted away (Denhart 2009).

There is a growing awareness in society, and in the built environment professions, of the environmental, social and economic benefits of applying a circular economy approach to management of the built environment (MacArthur, 2013). A circular economy is defined by the European Parliament (2021) as;

> a model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products as long as possible. In this way, the life cycle of products is extended.

The circular economy model provides environmental sustainability benefits including reductions in landfill waste, environmental degradation, and biodiversity loss. It also reduces greenhouse emissions by reducing the need for production and transportation of materials; economic sustainability benefits arise as lower costs result from reusing and repairing building components; and social sustainability benefits arise through employment and retention of existing fabric and structure of heritage buildings (Foster, 2020). The adoption of a circular economy approach acts as a driver to minimise waste (Mahpour, 2018).

The relevance of the discipline of materials conservation

The discipline of materials conservation is founded on the assumption that old and damaged materials can hold significance and value, and that care can preserve and enhance those values. In times of disaster, when so much is lost, there is strong potential to use materials conservation to help return a sense of control, continuity and connectedness to people and communities by preserving physical items from the time before the disaster. This is the mission of organisations such as Blue Shield (https://theblueshield.org/), and of the many conservators and organisations who donate their time and skills in the aftermath of disasters.

Most of these efforts, however, are focused on items or collections of special significance. We would like to apply conservation techniques and approaches to the broader "personal heritage" of homes and possessions that are not in themselves precious, but that together provide a sense of place and embody and express the ambience of lives and families over time. In particular we are interested in personal materials and general household surfaces that are not actually burnt, but which are in the fire affected zone and therefore become covered in the ash residue that settles out from the smoke of the fires (Fernandes et al 2003). This is typically a thin layer of black material that is unpleasant to look at, transfers readily to other materials and releases gases that smell unpleasant and have the potential to cause respiratory irritation and other health problems (Harms et al, 2021), and may provide anxiety inducing reminders of the fires.

If a cleaning solution is able to remove this ash layer in a short time window after the disaster, it will be possible to enable people affected by fires to return to their homes sooner, to regain a sense of empowerment and control over their lives by reconnecting with their physical surroundings and possessions, and to focus on cleaning and repairing rather than discarding still-viable materials. These aims align with the Sustainable Development Goals (United Nations Department of Economic and Social Affairs, n.d.), in particular goals 3 (good health and wellbeing), 11 (sustainable cities and communities), 12 (responsible consumption and production), 13 (climate action) and 17 (partnerships for the goals).

The potential of lasers

One of the techniques that has potential to remove this ash layer quickly and efficiently is conservation laser cleaning. Lasers have been used in conservation for many years, both for detailed cleaning for high value heritage objects, and for large scale work on buildings and sculpture (Anglos et al. 2006; Teppo 2020). Lasers require only electricity to run, so could be deployed quickly in fire affected areas, even running off a generator or solar power if power has not been restored (Martin Cooper, pers. comm. 19.11.2021). They use light energy to clean, so do not require the introduction of abrasives or other chemicals, or physical touching or abrasion of the surface. Dirt layers are ablated as a particulate "smoke" that can be captured and filtered by an extraction system, which minimises the waste disposal challenges of recovery in fire affected areas.

In applying this technique to bushfire affected everyday heritage we are aiming to take advantage of the precision that lasers can provide for removing thin dirt layers, to achieve a process that is relatively fast and efficient. We hope eventually to identify recommended treatment regimes that can be applied to a range of typical household surfaces, thus reducing the need for in situ experimentation to fine tune the laser treatment for each surface. The desired outcome is not a surface that is perfectly clean, but a surface that is sufficiently clean for repair processes such as sanding, repainting or revarnishing.

Practical considerations

The authors note that the scope of this paper is to demonstrate that lasers can effectively remove layers of ash from a common household substrate (in this case painted plasterboard) without damaging the substrate. Practical implementation of laser cleaning in fire affected properties is beyond the scope of this paper as it will involve trialling and evaluating solutions to a number of practical issues, as well as comparison with the efficiency and effectiveness of existing approaches. To provide context for the experimental work presented in this paper, however, we will briefly outline below the implementation issues that we foresee.

Many of the processes required to implement safe laser treatment have analogues in existing remediation practices and therefore will not impose an additional time/cost burden. The true costs of many existing practices are also not factored into the financial cost of remediation (such as the environmental impact of waste), so both positive and negative costs for both laser and traditional remediation processes need to be taken into account when assessing the positive potential of laser use.

Work is required to isolate a site for remediation: Traditional approaches usually involve the placement of fencing around the site. Laser cleaning also requires the operator to ensure that the laser beam cannot escape the work area, or be reflected, at a power level that would cause harm to people who are not protected by appropriate PPE. This might require covering of reflected or translucent materials, or the fitting of a temporary interlock system to shut down the laser if someone enters the work area (Smalley 2011).

Work is required to prepare spaces and surfaces for remediation: Traditional approaches include removal of bulk dirt deposits, materials that are too badly affected to be cleaned (in particular soft materials which may be charred, melted or saturated with volatile chemicals from the smoke), and furniture and other items that are in the way. All of these actions would be needed in preparation for laser cleaning, as well as covering of reflective or translucent surfaces to prevent reflection or escape of the laser beam. Some items that have been removed may be able to be cleaned separately, which can further engage the expertise of materials conservators.

Work is required to ensure that workers are protected from potential hazards: Lasers are regularly used to clean general dirt and graffiti from heritage buildings and monuments, so practices established in this field can provide guidance in this area (Cooper 2005). In common with traditional remediation practices, correct Personal Protective Equipment (PPE), ergonomic, and work duration practices will need to be used, with laser safety goggles that filter out the wavelength(s) of light produced by the laser being a primary requirement. As with many traditional remediation processes that create dust and fumes, laser cleaning requires an extraction system to remove ablation products, which would need to be integrated or synchronised with the laser head. Depending on the toxicity of the residues, ablated material might be exhausted externally or captured in a filtration unit. Extraction is also important to reduce energy absorption by ablation products, thereby ensuring optimal performance of the laser (Smalley 2011).

Informal conversations with residents of coastal towns in New South Wales (NSW) suggest that many people have been washing surfaces themselves with products such as sugar soap, baby bath and wool wash detergents and products sourced from local hardware stores (residents of Nerriga, NSW, pers. comm. 18.02.2021), and the builders who remediated the property our samples came from also washed some areas with Actichem Firefix, an alkaline cleaning solution (pH 9.5-10.5). The aim of laser treatment is not to replace this low-cost washing process, but to encourage cleaning rather than replacement for surfaces that builders currently deem unfit for retention, (such as the plasterboard used in this project which is ash-covered but still structurally sound – see Fig 1). In future work we intend to analyse the components of bushfire ash to check for toxic compounds, and compare exposure levels generated by traditional washing and laser cleaning.

Optimising and automating lasers for bushfire and other disaster clean-up: nanosecond (ns) and femtosecond (fs) lasers have been tested in this project. Portable nanosecond lasers are already available for both heritage and industrial cleaning, in tabletop, freestanding and backpack units. Femtosecond lasers are more expensive and not yet available in portable packages, but market interest in their application suggests that portability and lower prices will become available in the future.

Automation of the laser cleaning process is already standard in experimental and manufacturing contexts and work has been done by the University of Technology Sydney Centre for Autonomous Systems on a robotic mount to move a laser head around a heritage structure with optical fibre delivery, scanning system and extraction system (Dai et al, 2021;

ABC News 2016). As well as reducing worker exposure to hazards, an automated system would be able to work continuously, thus reducing remediation backlogs (Somerville 2021). Real time analysis of the ablation plume with Laser Induced Breakdown Spectroscopy (Kono et al 2015) could ensure an automated system would stop or move on once cleaning had reduced characteristic compounds of the dirt layer to a specified level.

This work is therefore a first step in imagining new ways of managing remediation and recovery of properties after bushfires, and potentially other disasters that result in the deposition of dirt.

Methodology

Sample description and condition

Samples of painted plasterboard were obtained from a house that had been partially burnt during the 2019 bushfires in the coastal area of south-eastern Australia. Smoke from burnt materials circulated through the house and as it cooled and dissipated ash precipitated out on surfaces, including the painted plasterboard of interior wall surfaces (See Fig. 1). The ash layer is thin but the plasterboard surfaces have a deep grey colour with a strong, smoky smell. Apart from the ash deposition, however, the plasterboard is structurally sound and in good condition.

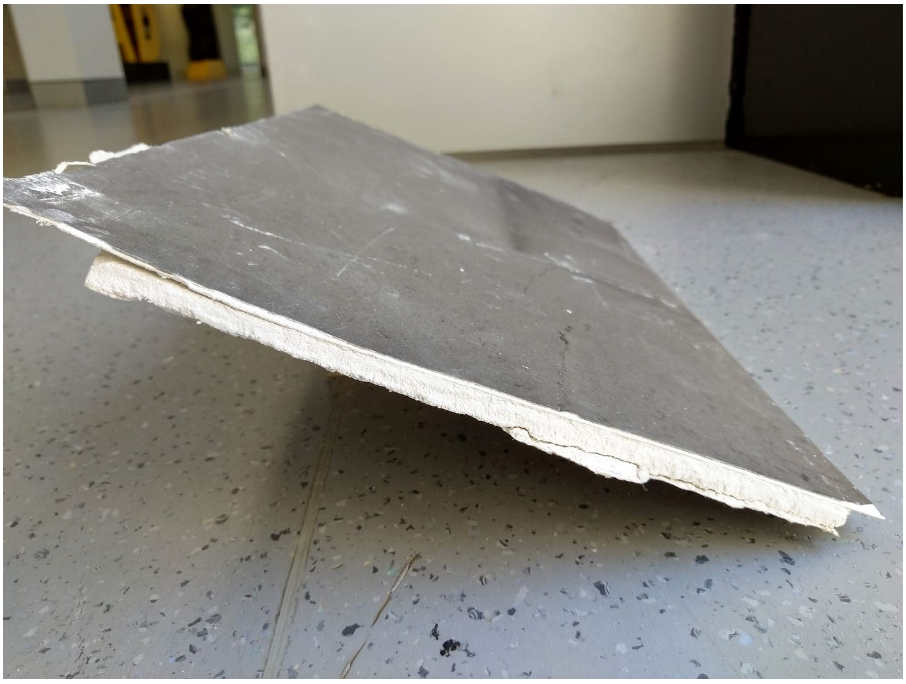


Figure 1 – Plasterboard sample removed from house by builders. While the interior wall surface is coated with a thin layer of ash, the rest of the board is in good condition.

The samples were removed from the house 14 months after the burning took place, during which time the affected areas had been sealed up to prevent entry from agents of deterioration such as rain, animals and vandals. At this stage they smelt strongly of the smoke from the fire. After the samples were removed from the house and kept in ambient air in the laboratory, the smell dissipated quickly (though we did not have the opportunity to measure changes in off-gassing objectively), but the colouration of the ash layer remained. The remediation contractors advised that this would make it difficult to repaint with good adhesion and good replication of the pre-fire white colour.

The samples consisted of a layer of plasterboard, covered on both sides with a paper surface. On the side that faced into the room, the paper surface was covered by several layers of paint, the lower layers being an unknown blue paint and the top layers being a white interior acrylic paint marketed by Haymes Paint (Silkworm, Taubmans Spectrum Fandeck, Elite, Interior Low Sheen, Tint formula B – 1Y, 12, 0; C – 0, 22, 48; F – 0, 11, 28). Additionally, samples of the original paint (retained by the homeowner) were painted out on cardboard to provide comparison with the ash coated and laser cleaned samples.

The aim of the test treatment was to remove the deposited ash from the surface to expose the white paint in clean condition, ready for repainting. Our criteria for success were to:

- Remove the blackened colour sufficiently to allow repainting in a light colour without the blackened colour showing through;
- Remove poorly adhered dirt that would prevent good adhesion of the new paint;
- Allow fire affected material to be reused, thus saving time, reducing new materials required, reducing costs, reducing landfill, and providing the home-owners with a sense of valuing and caring for the personal heritage embodied in the fabric of their home.

Laser treatment

This paper explores the potential of ns lasers (which clean through heat related and shockwaves effects) and fs lasers (which can clean by breaking molecular bonds directly – the so-called "cold ablation" process) for removing bushfire related ash deposits from household materials. Nanosecond lasers are currently the most available laser cleaning systems for the conservation market and they use pulse durations of 100 ns or longer. At these pulse lengths the laser light generates heat and shockwaves that either vaporize the dirt layers or explosively dislodge them from the underlying surfaces (Rode et al, 2006). Despite being effective (discussions of the effectiveness of ns lasers can be found, for example, in Siano et al 2012, and in the proceedings of LACONA "*Lasers in the Conservation of Artworks*" conferences) these types of laser are known to generate considerable heat in the objects being cleaned, potentially causing changes in the morphology, chemistry, and internal structure of the materials and underlying layers. These can include heat-related physical and/or chemical changes in the surface and bulk material properties, formation of cracks (Zinnecker et al, 2022), exfoliation of flakes from the surface, and annealing/softening of thinner sections of the bulk material. The heat effects also make it difficult to accurately control the depth and precision of the cleaning procedure.

Femtosecond lasers (also known as ultrashort or ultrafast pulse lasers) potentially provide a solution to this problem, as their pulse durations are so short that the ablation proceeds in the skin layer of the material only, without heat transfer into the bulk of the material, through a process known as electrostatic ablation (a detailed explanation of this process for the non-physicist can be found in Rode et al, 2006; see also Gamaly and Rode 2013. Papers describing the use of femtosecond lasers for cleaning include Burmester et al 2005; Ersoy et al 2014; Maharjan et al 2017.). This enables rapid laser cleaning of surfaces without detrimental thermal and shock-wave effects on the underlying material, and as the process does not involve the diffusion of energy as heat, the efficiency of cleaning is not affected by whether the surface being treated is of a light or dark colour. Each fs pulse removes a very small amount of material, and by scanning the surface repeatedly the laser can ablate material to a precisely selected depth. This offers significant advantages for maintaining safety and integrity and preserving the original strength of the material to be cleaned. The treatment can be stopped at controlled depths through the paint/material layers, and can provide either a smooth or a stippled texture, the latter promoting the adhesion of new paint.

Both lasers being trialled operate in the infra-red region, the ns laser at 1064 nm and the fs laser at 1029 nm. These wavelengths are close enough that absorption of the laser energy by the treated materials can be considered similar, making pulse duration the major point of difference between the performance and impact of the two laser types.

Experimental setup for nanosecond laser treatment

Ns ablation experiments were carried out with an Nd:YAG nanosecond laser (Compact PHOENIX Laser System from Lynton Lasers, United Kingdom), using its fundamental wavelength of 1064 nm. The pulse duration is 5 ns (Lynton Lasers, 2019), and the maximum output power is 1.15 W. The unit was operated at 5 Hz repetition rate and 230 mJ pulse energy. The ns laser ablation was performed in ambient air and pressure.

The Compact Phoenix laser is normally delivered as a handheld beam, which in practice results in a variable distance from the target material. This means that the laser beam spot size will vary, and therefore change the applied laser fluence at the surface. To keep the energy deposition on the target constant from pulse to pulse and to allow precise comparison with the known fluence provided by the automated scanning system of the CB3-40W fs laser, the Compact Phoenix handpiece was mounted on a cradle and the sample placed on a Y directional moving stage to provide consistent scan speed and distance from the target material (Fig. 2a). The distance from the optical fibre output to the image on the sample surface was 200 mm, providing a spot size of 5 mm diameter and a laser fluence on the target of 1.17 J/cm^2. After initial trials two scan speeds were selected for further exploration – 8.75 mm/s and 17.5 mm/s, which provided respectively 45% and 50% overlap between spots on the surface. For extended cleaning trials, after each Y run, the sample was manually moved in the X direction to provide approximately 50% overlap between adjacent runs.

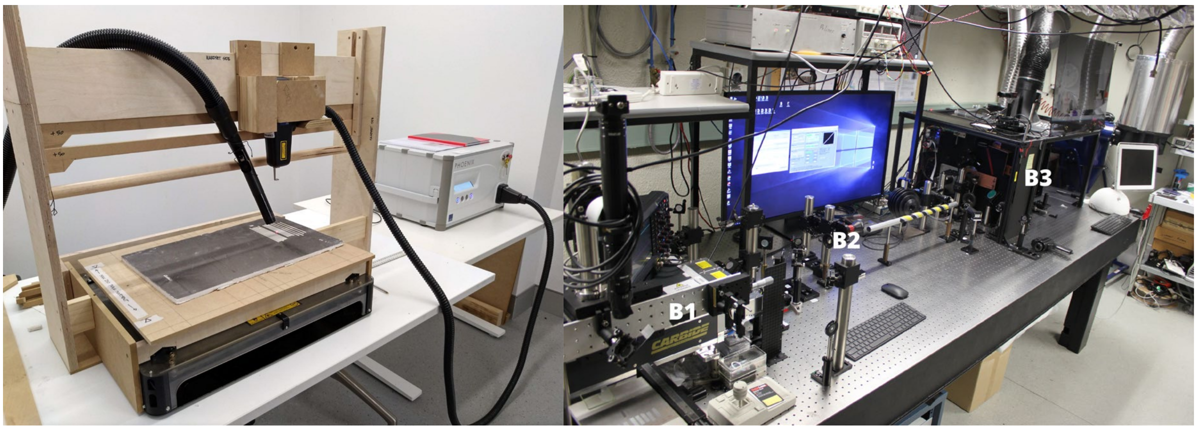


Figure 2. Experimental arrangements for the ns and fs lasers. Note that these are laboratory experimental arrangements only and do not reflect the configuration of a system for practical onsite use. (a) LHS – the Compact Phoenix ns laser setup. Normally an operator would use the handpiece freely, but to allow comparison of the performance of the ns and fs lasers the handpiece was mounted on a cradle and the sample placed on a moving stage; (b) RHS – the Light Conversion fs laser setup: B1= the laser unit; B2 = the beam path; B3 = the sample (contained within extraction unit housing)

Experimental setup for femtosecond laser treatment:

Fs ablation experiments were carried out using a Carbide 40W fs laser (CB3-40W from Light Conversion, Lithuania), using its fundamental wavelength of 1029 nm (Fig 2b). The pulse duration was set to 275 fs at up to 1 MHz maximum repetition rate and up to 0.4 mJ in energy (at 100 kHz). For beam scanning, a 10-facet polygon mirror (Precision Laser Scanning Inc., USA) (y-direction) and a galvanometer scanner (Cambridge Technology Inc., USA) (x-direction) were used. This enabled beam speeds of up to 880 m/s across a maximum scan area of 280 x 280 mm at 52% duty cycle per polygon scan line for the laser, the beam speed being sufficiently high to operate in the single shot per spot regime and so avoid possible accumulation effects.

The laser pulses were focused on the sample with a quasi-telecentric f-Theta scanning lens of 540 mm working distance (S4LFT1420/449, Sill Optics GmbH, Germany). The focal spot diameter for the raw beam was ~87 µm at full width half maximum (FWHM). To form a spot with a well-defined square shape, the Gaussian beam profile was transformed using a beam shaper based on a diffractive optical element (DOE), a square flat top hat beam homogeniser. The square flat top hat profile presents a homogeneous fluence on the entire square top region with a beam size of 165 x 175 μm^2. The ablation was carried out using100 kHz, 1000 rpm, a beam step of 10 µm, and a pulse energy of 380 µJ, and the range of fluence investigated was 0 to 4 J/cm^2. The fs laser ablation was performed in ambient air and pressure.

Results of laser treatment

Both the ns and fs treatment regimes met the criteria for success; they removed the blackened ash layer while leaving substantial amounts of the white paint beneath (Fig. 3) to provide a clean, light-coloured surface that is likely to be appropriate for repainting without further preparation (this will be tested in future experiments).

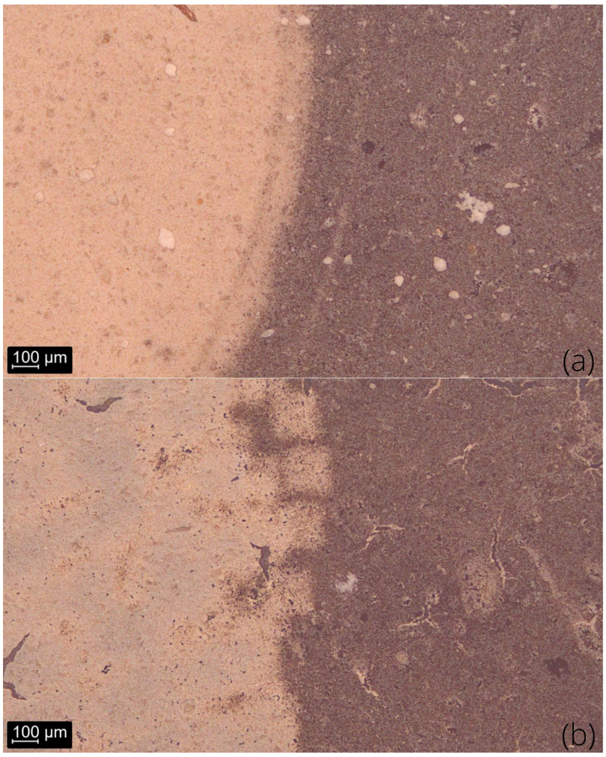


Figure 3. Edge of cleaning tests showing effect of removal of ash deposits: a) ns laser with a 5 mm diameter circle spot size; b) fs laser with a 165 x 175 μm^2 spot size. Images taken using a Leica DM2700 M optical microscope in reflected light mode at x5 magnification.

For the ns tests, the faster laser scan time (17.5mm/s ns) proved to be more efficient, taking less time and energy to remove the ash layer, and leaving more of the white paint in place (Fig 4).

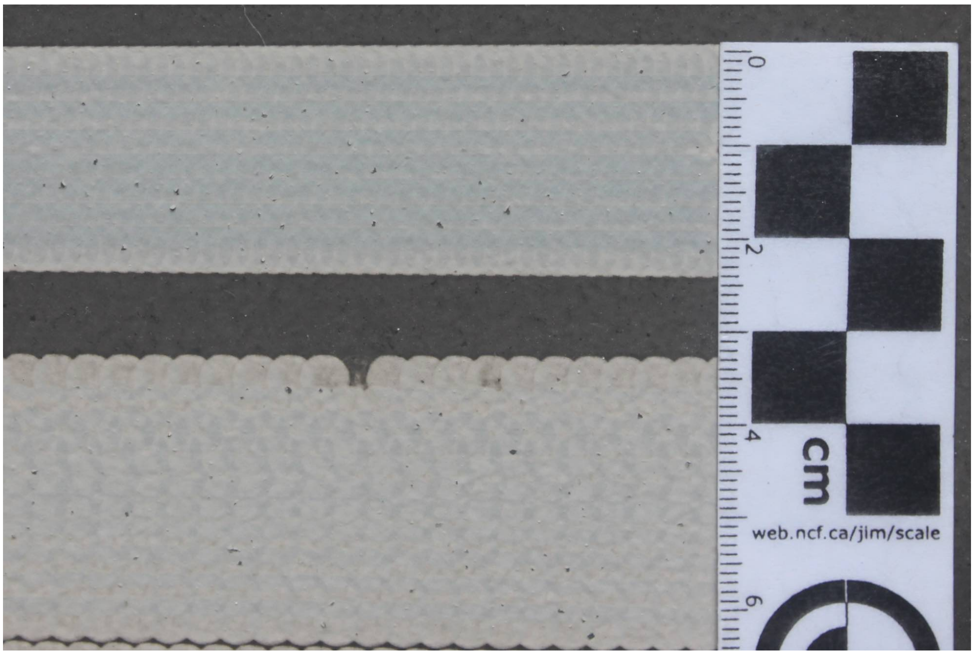
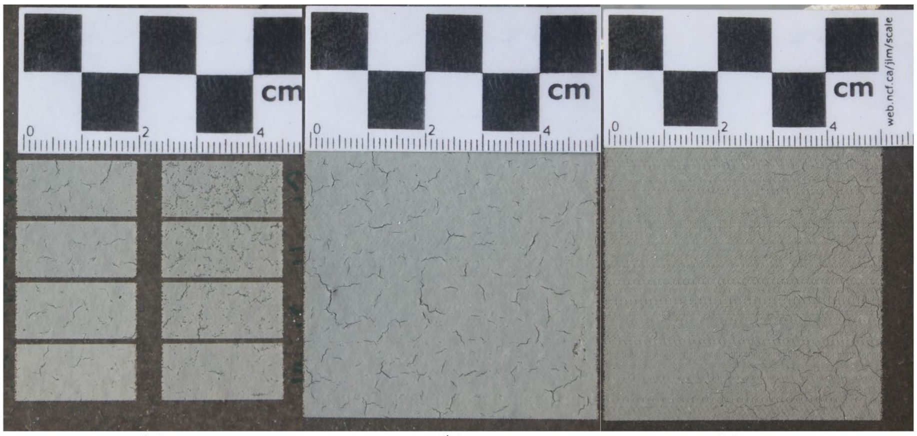


Figure 4. Results of cleaning with ns laser at 1.17 J/cm^2. The top strip was completed using a scanning rate of 8.75mm/s, and the bottom strip using a scanning rate of 17.5 mm/s. The bottom strip shows a more efficient regime, taking less time and energy to remove the ash layer, and leaving more of the white paint in place.

In the fs tests (Fig. 5) the fluence level (threshold) that started removing the ash layer was found to be 0.17 J/cm^2. At 0.40 J/cm^2, one pass resulted in the white paint being visible, but showing a brownish colour, meaning the ash layer was not totally removed. A fluence of 0.70 J/cm^2 cleaned the paint back to a white colour. At higher fluences, a blue tint started to become apparent. Some of the fs laser trials show small cracks in the surface of the white paint. This does not seem to be a result of the laser cleaning, but of the initial heat exposure during the bushfire, as the cracks only appear in areas of the sample which also show darkening of the paper surface of the plasterboard (under the paint layers) and isolated blistering of the paint surface. Fig 5c shows that the cracks are only evident close to these more heat exposed areas of the sample, and that they disappear in areas that were less heat affected.



(a) (b) (c)

Figure 5. Results of cleaning with the fs laser: (a) surface varying the laser fluence from 0.20 to 3.10 J/cm^2; (b) larger test patch using just one pass at 0.70 J/cm^2 ; (c) cracked and non-cracked paint in the same trial patch.

The larger spot size of the ns laser leaves a distinct patterning on the treated surface (Fig. 4): this should not be a problem as the aim of the treatment is to provide a surface suitable for repainting, and therefore texturing may assist new paint to adhere well. Slight patterning was also observed in some of the fs treatments (this can be seen, for example, on close inspection of Fig 5c).

To gain an idea of the overall speed of the laser treatments at the scan rates, fluence and spot sizes used in the trials, the time taken to complete the test patches was used to calculate an approximate time for the treatment of 1 m^2 of plasterboard surface. The ns laser would take approximately 118 minutes (almost 2 hours) at the 8.75mm/s scan rate, but only 53 minutes at the 17.5mm/s scan rate. The fs laser would take approximately 64 minutes with the scanning rate used. The scan rates that proved most efficient at cleaning the plasterboard therefore resulted in a similar treatment time for both types of laser, with the ns laser being slightly faster.

Analysis

FTIR and visible light spectrophotometry analyses were undertaken to provide an objective evaluation of the results of laser cleaning.

FTIR tests and results

FTIR analysis was undertaken to assess the difference between the fresh white paint (an interior white acrylic painted from retained cans of the original paint), the ash covered surface, and the white paint after cleaning with the ns and fs lasers (Fig. 6). The FTIR spectra were obtained with a Perkin Elmer Frontier FT-IR/NIR spectrometer using an attenuated total reflection (ATR) stage and showing the results in absorbance mode.

Fig. 6 shows that the spectrum for the ash covered surface was surprisingly similar to both the fresh and the cleaned samples. In fact, all the peaks in the fresh paint sample are present in the ash covered sample, which may suggest that the ash layer was thin or discontinuous enough for the FTIR beam to be reading both the ash layer and the acrylic paint underneath. There are some differences in the intensities of the peaks, which probably represent different levels of contribution to the spectrum between the different spectra at these wavelengths. Particularly noticeable are a group of 3 peaks just below 3000 cm^{-1}, and a sharp peak at 1617 cm^{-1}. Wang et al (2013), in a study of ash deposition (for which they use the term "soot") during diesel combustion, note that the group of peaks just below 3000 cm^{-1} are C–H stretching features that correspond to aliphatic groups, and a similar peak at 1620 cm^{-1} corresponds to an aromatic C=C stretching vibration. Wang et al demonstrate that differences in the ratios of these features are related to differences in combustion conditions and the consequent deposition of either a disordered soot structure with more aliphatic groups on the surface, or a more ordered soot structure with less aliphatic groups. The lower intensity of all these peaks in the fresh and cleaned samples suggests that in the absence of, or after reduction of, the ash layer, contributions to the spectra at these frequencies are predominantly limited to compounds found in the paint itself.

There is also a large difference in the different spectra in the intensity of the peak at 1110 cm^{-1}. This peak represents C=O stretching, which Wang et al (2013) relate to the partial oxidation of soot. This might explain the high intensity of this peak found in the spectrum of the ash covered paint in the current study. Ormsby et al (2009) also relate this peak to the use of surfactants as emulsifiers in artists' acrylic paint formulations. They note that surfactants tend to migrate to the surface of acrylic coatings, and observed a drop in peak size after aqueous cleaning to remove surfactant. Contributions to this peak from surfactants at the paint surface may account for the presence of this peak in both the fresh and cleaned paint samples in the current study, while the reduction of the peak intensity between the fresh and cleaned samples may indicate removal of surfactant compounds during the cleaning process.

Cogulet et al (2019) studied the deterioration of two acrylic exterior wood paints and noted that photodegradation mechanisms, including chain scission, degraded the polymeric structure of the paints and produced low molecular weight molecules. This produced a reduction in the intensity of a number of peaks, especially through the 900-1500 cm^{-1} fingerprint region, and at 1726 cm^{-1}. In the current study, peak intensities are very similar for the fresh paint and ns cleaned spectra, but the peaks in the fingerprint region for the fs cleaned sample are significantly lower (with the exception of the peaks at 1421 and 873 cm^{-1} which Cogulet et al relate to the presence of a $CaCO_3$ extender rather than bonds within the polymeric structure). This raises the possibility that the fs laser, which cleans by breaking bonds directly through the electrostatic ablation process, is causing more degradation of the white paint than the ns laser. Further work will be required to explore this possibility.

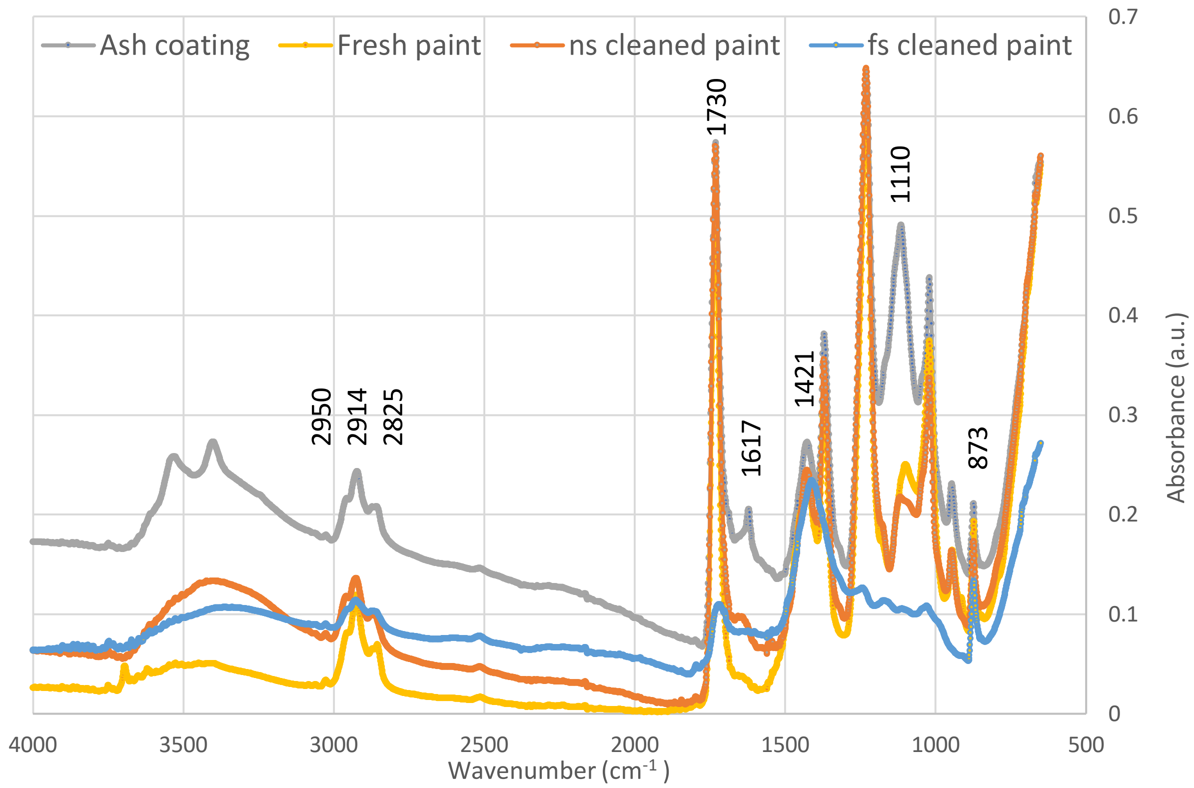


Figure 6. Comparison of FTIR spectra: ash coated surface, fresh paint on cardboard, and ash coated samples cleaned with the ns laser at a scan rate of 17.5 mm/s and fluence of 1.17 J/cm^2, and with the fs laser at a fluence of 1.73 J/cm^2.

Colour measurement

Colour readings before and after laser treatment were taken to provide a record of the colour change achieved through laser cleaning, and to put objective values on the differences between the colours obtained by cleaning with the different laser types and conditions (see Table 1). The readings were taken using a Konica Minolta CM-2600D spectrophotometer using the CIEL*a*b* colour space; illuminant D65; standard observer angle 10°; UV 100% of Xe flashlight source and measurement diameter 8 mm. ΔE* values were calculated using the online CIE2000 Calculator (http://colormine.org/delta-e-calculator/cie2000). In the CIEL*a*b* system L* indicates lightness, a* is the red/green coordinate, and b* is the yellow/blue coordinate. Delta E (ΔE*) calculation is used to determine the difference between two colours (Konica Minolta, n.d.).

Table 1: Spectrophotometer readings taken before and after laser treatment.

	Surface measured	**L* (SCE)**	**A***	**B***	**ΔE* (difference between two colours)**
Row 1	Ash coated paint	44.70	1.67	4.30	
Row 1	Fresh paint	100.1	1.03	-0.44	ΔE* compared to ash coated paint 41.8484

Row 3	Patch cleaned with ns laser (see Fig. 4) at 8.75 mm/s scan rate	85.97	-0.82	2.79	ΔE* compared to fresh paint 9.4707
Row 4	Patch cleaned with ns laser at 17.5 mm/s scan rate (see Fig. 4)	88.69	0.03	4.99	ΔE* compared to fresh paint 8.5409
Row 5	Patch cleaned with fs laser (see Fig 5b)	63.78	-1.34	3.10	ΔE* compared to fresh paint 25.0204

The ΔE* calculations show the large difference in colour between the deposited ash and the fresh paint. The comparison of the cleaned patches to the fresh paint sample also show that cleaning with both laser types returned readings much closer to the original white paint colour, with the ns cleaned patches being the lightest in colour. The colour produced by cleaning with the ns laser was also visually creamier, with that produced by the fs laser being slightly bluer in tone (sometimes quite strongly) and further work is needed to discover the mechanisms and thresholds at which the blue colour is produced. As the colour criterion for success in this project is to remove the blackened colour sufficiently to allow repainting in a light colour without the blackened colour showing through, however, the exact shade of white is unlikely to be critical.

Conclusion

The results obtained in this preliminary study have achieved the criteria for success established in the Methodology section. Both ns and fs lasers successfully removed the bushfire ash layer from the fire-affected plasterboard and revealed the original white paint. In doing this they produced a clean, largely intact surface which should be suitable for repainting (an assumption that will be tested in future experiments). The return of the surface to a light colour will also allow repainting in new layers of white paint, without the problem of darkened layers showing through.

As well as preparing materials for repair, the removal of the blackened colour of the bushfires will help facilitate a return to a sense of normality for people who have survived the devastation of bushfires. It is hoped that further work will be able to confirm that the laser cleaning has also been able to remove the smoky smell left by the fires, which is both unpleasant and can cause ongoing respiratory problems.

Overall we believe the ns laser performed slightly better:

- It produced a cleaned paint surface that was both lighter (higher L* value) and creamier in hue (a* and b* values) than that produced by the fs laser;
- The FTIR spectrum for the ns cleaned paint was closer to the fresh paint than the spectrum for the fs cleaned paint, suggesting that less chemical change occurred during cleaning;
- Under our trial conditions the ns second laser was faster than the fs laser when using a scan rate of 17.5 mm (treating 1 m^2 of surface in 53 minutes as opposed to 64 minutes for the fs laser). COVID lockdowns, however, restricted our ability to investigate alternative setup and power conditions with the fs laser, and future work will be needed

to investigate the potential to gain faster processing time using bigger spot sizes and higher scanning speeds.

- Further tests are needed to investigate the ability of both lasers to remove ash from dark (as opposed to light) underlying paint, their ability to remove residual smoke smells, and the ability of the cleaned areas to be successfully repainted.
- Futher work is needed to compare the time-scales and visual results of laser cleaning with more traditional methods of domestic ash (soot) removal.

In terms of practicalities the ns laser is also currently commercially available at a reasonable cost in a robust, portable package which can run on domestic power networks and generators. fs lasers require substantial development to get to this stage.

Implementation tests will be needed to determine whether an automated system or a handheld system will give the best results when used to clean an actual home. An automated system would provide precision, reduce human exposure to ash, and reduce time and discomfort for a human operator. It would, however, require a robotic head to move the laser around, and might struggle with 3D shapes and long distances to the target surfaces. A handheld system would be less precise but more versatile, but would require careful management of PPE, time and ergonomics to ensure the safety of the human operator. The ns laser is currently available with a handheld fibre optic delivery system. Fs lasers are currently only available as beams that are guided using automated scanning software, although we are currently exploring the potential to develop a portable fs laser system, with either a handheld or automated delivery system.

Use of a laser system in a disaster affected areas would also need extraction for fumes and particulates, a portable setup for preventing the laser beam from escaping beyond the work site, and the operator would need to check for lead and any other hazards that might affect the cleaning operation. As lasers have been used for the remediation of heritage buildings and outdoor sculpture and other objects for many years, however, solutions for these issues already exist. In a remote, bushfire affected area power may be an issue, but the Compact Phoenix is able to run on any power supply that can provide 200-264 V AC, an operating current of 5 A @ 240 V, VA Rating 1.2 kVA maximum and an operating frequency of 50 Hz or 60 Hz. This makes it able to run on a generator and potentially also a solar powered system (Martin Cooper, pers. comm. 19.11.2021). Jason Church of the US National Parks Service reports having successfully used the unit with a Honda gas powered power invertor (pers. comm. 30.11.2021)

Conventional cleaning methods used for bushfire impacted buildings are mainly based on physical abrasion, manual removal and disposal to landfill. In contrast to these approaches the method described in this paper has the potential to be transformative, achieving more efficiency, reduced waste and supporting the recovery not just of the physical fabric of homes and lives but the intangible benefits of personal and community heritage.

We recognise the challenge of developing a system that would be robust and readily usable in a post-disaster situation, and acknowledge the need to compare its performance with existing cleaning and remediation systems using a range of qualitative and quantitative metrics. Nevertheless, we hope that this challenge will provide the motivation to develop new attitudes to, and practical techniques for, disaster remediation that minimise waste and encourage recovery by respecting and caring for the personal heritage held in people's built environments.

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Declaration of interest

The authors declare that they have no financial interest in or benefit from the direct applications of this research.

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