A comparison of ultrasonically activated water stream and ultrasonic bath immersion cleaning of railhead leaf-film contaminant

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Abstract

Leaf-film adhered to the railway track is a major issue during the autumn/fall season, as leaves fall onto the track and are entrained into the wheel-rail interface. This results in the development of a smooth, black layer. Presently, pressure washers must be used to clean the residue to prevent loss of traction, which can cause crashes or delays by forcing a reduced speed. These pressure washers consume large amounts of water and energy. In this study, use of an ultrasonic cleaning apparatus equipped with a 100 W transducer is investigated, using a low volume of water in the order of 1 L min^{-1}. This was applied to leaf-film samples generated in the laboratory, whose surface properties and thickness were confirmed with optical and stylus profilometry methods. Cleaning achieved by an ultrasonically activated water stream was compared to a) non-activated water and b) an ultrasonic bath with comparable power consumption. Cleaning efficacy was found to be much greater than that afforded by the ultrasonic bath; a rate of 14.3 $mm^2\ s^{-1}$ compared to 0.37 $mm^2\ s^{-1}$, and the ultrasonic bath only cleaned off around 20% of the leaf-film coverage even after 3 minutes of exposure.

Introduction

Ultrasonic irradiation of a liquid medium is commonly employed in academic, medical and industrial environments to clean materials. The interaction of sound and bubbles can produce many physical or chemical phenomena which interact to remove contaminants from the surface; cavitation resulting from bubble collapse; formation of shear waves; the formation of microjets; erosion, or sonochemical production of oxidants resulting from the dissociation of vapour (Rooney 1970; Maisonhaute et al., 2002). The most common form of its application is the use of ultrasonic cleaning baths. However, this technology has many limitations: the object to be cleaned may not exceed the size of the bath; sizeable and heavy objects may affect the sound field developed in the bath and reduce its efficacy, resulting in 'hot' or 'cold' spots in the bath geometry, such that small areas remain uncleaned; the extreme difficulty in cleaning complex geometries or very rough samples; and the accumulation of non-soluble contaminants in the cleaning medium, which can potentially be redistributed to other specimens, or other areas of the same specimen.

Recently, a novel cleaning system has been developed that uses the acoustic activation of bubbles within a free flow, low pressure (5 bar or less) stream of water to generate an ultrasonically activated stream (UAS) (Leighton et al. 2011, 2013; Birkin et al., 2015a/b). The device allows for an efficient transfer of acoustic energy within the water stream, allowing the cleaning activity to be separated from the transducer. The forces acting on individual gas bubbles cause them to coalesce and scour the surface, or be pulled towards troughs between asperities on the substrate (Leighton et al. 1988; Leighton 1994; Doinikov 2001; Stricker et al. 2013). At the surface interface, the cavitation dynamics of the bubbles induce convection (Offin et al 2007) and local shear waves, both acting on the surface contamination and cleaning it in an efficient manner (Rooney 1970). In particular, the cleaning activity produced by the bubbles at the surface results in superior cleaning of contaminated troughs which remain uncleaned even after extended exposure to a water stream (Offin et al. 2014).

The first commercialisation of this technology, StarStream® (Ultrawave Ltd.), has proven particularly effective for cleaning rough surfaces, as demonstrated by Howlin et al. (2015). In the former study, dental bacterial biofilms were removed from contoured surfaces using the ultrasonically activated stream. It also significantly enhances the performance of additives to remove oil and grease, although not the goal of the present study (Leighton, 2015).

StarStream is designed to place microbubbles at the end of a stream of water, such that where the stream of water (of approximate cross section 1 cm^2) impacts the target to be cleaned, those microbubbles are activated by ultrasound and generate shear on the surface. This shear provides an effective cleaning effect. The ultrasound is generated by a transducer and coupled to the stream of water by a horn. Cleaning can even be achieved using only cold tap water, without additives, unless the contaminant is oily or greasy.

In the present study, the applicability of UAS technology to railway traction issues is being explored. During the passage of a train over a rail section, leaf-fall from nearby trees is entrained within the contact patch and crushed into the asperities on the railhead, essentially smoothening the rail surface (Poole, 2007). The generation of leaf layers and the low friction conditions have been the subject of various studies (e.g, RSSB's GM/GN2642 and 2643 reports; Zhu et al, 2014) This film-forming process is responsible for the familiar 'leaves on the line' problem known in the industry as the 'Adhesion Riddle'. This phenomenon costs the UK rail industry ~£50 million each autumn owing to the potential loss of traction between wheel and rail, meaning that speed must be reduced and delays incurred to avoid potential accidents resulting from decreased braking performance. Multi-purpose vehicles (MPVs) equipped with high pressure water jets, operating at around 1500 bar, are deployed to remove this contaminant. These necessitate a very large volume of water to be carried in tanks, though they set a precedent for the use of water to remove contaminants bound to the railhead. Alternative methods include dispensing sand and traction gels using MPVs in much the same manner. Here, we explore a proof-of-concept for a novel cleaning method, to determine if a possible application in this area can be found, either as a hand-held device or mounted on MPVs.

Asperities on the rail-head exist on the order of microns to tens of microns with a typical Ra in the order of 1 µm, and are typically slightly negatively skewed as one would expect from a heavily loaded and worn surface; i.e. the troughs tend to be deeper than the peaks are tall (Rsk = - 0.3 to -1).

Experimental

The cleaning setup comprised a commercial ultrasonic cleaning bath (Ultrawave Ltd., IND1750D) and commercially produced UAS system (Ultrawave Ltd., F0030001, StarStream; Leighton et al., 2013). The StarStream device used in this study is a handheld unit, taking cold water and being powered from the domestic mains supplies.

Rail-head samples were produced by cutting sections from used mainline commuter rail. Railhead leaf-film contamination on these samples was produced using a TE77 Plint reciprocating tribometer. Extensive experimentation yielded optimal conditions for reproducing consolidated leaf film with this rig. The maximum stroke length of 25 mm was used (to produce the largest area of coverage), at a frequency of 1 Hz, with slight heating to 30°C (which allowed quicker drying of pulverised leaf matter). Actual railhead samples proved to be more easily 'contaminated' due to mechanical locking with corrosion pits, while samples with mechanical machined surfaces proved much more difficult to 'contaminate'. A polymeric (PEEK) roller, with a width of 10 mm, was used to reduce the levels of adhesion on the roller surface, which proved problematic when a steel roller was used. Initial experimentation with whole leaves proved ineffective and leaf powder was made by blending whole leaves, with water (for lubricity to avoid clogging the cutting blade). The wet leaf matter was thoroughly dried over several weeks to paper type consistency. This allowed careful experimentation with the levels of hydration of the leaf matter to achieve adhesion, which was a ratio of around 4.5:1 (by weight) of dry leaf matter to distilled water. Rolling contact has to be maintained at all times since the development of sliding would destroy the film. In addition, the test protocol was optimised to: an initial load of 300 N and main load of 700 N, which corresponds to a Hertzian contact pressure of around 120 MPa. When the leaf-film was visibly consolidated the rig was stopped and the 'contaminated' sample removed for coverage determination. The mean consolidated coverage achieved was ~200 mm^2. The area of well-adhered material was determined by spraying the area using a hand-held spray bottle with distilled water. Poorly adhered material within the roller contact would be easily removed, as well as cleaning loose leaf matter from the surrounding area of the plate. An example is shown in Fig. 1.

Cleaning with the UAS device was carried out by holding it in a retort clamp with a stand-off distance of 10 mm, perpendicular to the sample surface, and a flow rate of 0.8 L min^{-1} of cold tap water. Tests with and without activation of the ultrasonic transducer were compared. During these tests, the sample was fixed to a stationary steel block and the water stream was guided over it, while the transducer was intermittently activated for set time periods. Cleaning in the ultrasonic cleaning bath was carried out by placing the sample at the centre, with no other objects present aside from the bath's own mesh that was used to support the sample. Cleaning exposure was carried out for up to 180 seconds, or until no further removal of contaminant occurred, with four to five repeats of each sample treatment performed. Coverage of the surface contamination was determined by intermittent photography of the samples, carried out after each short cleaning duration, followed by thresholding and binarisation of the images using ImageJ software to establish the real cleaning effect. Thickness of remaining leaf-film before and after cleaning was determined using tactile (Talysurf 120L stylus) and non-contact (Alicona G4 optical) profilometer measurements. The binarisation process used to determine coverage also measured corrosion pits, dirt and general grime on the rail head which is present regardless of leaf-film coverage. Typically, coverage from this pre-existing contamination on an area of rail was between 7-21%.

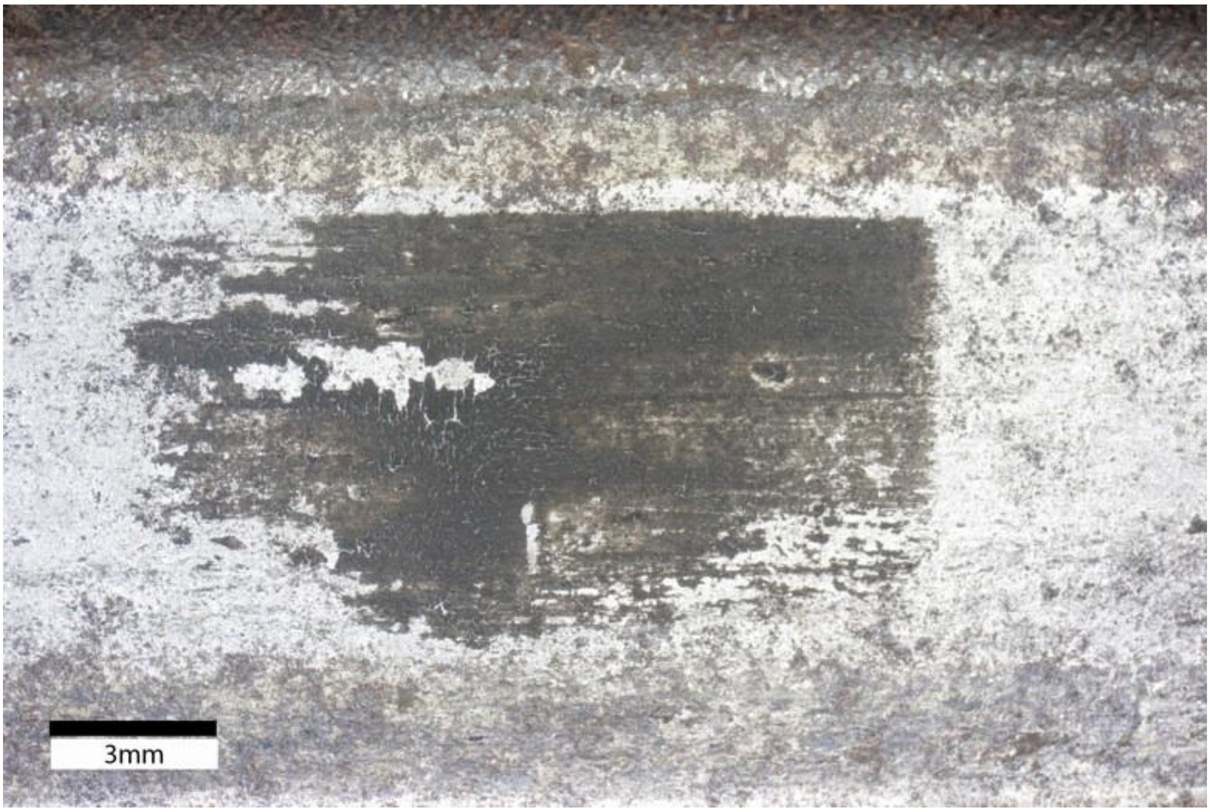


Figure 1: Example of railhead leaf-film produced in the laboratory.

Results and Discussion

In the case of the ultrasonic bath, a strong initial cleaning is observed, whereby an area of leaf-film is visibly dispersed within 1-2 seconds of activating the ultrasonics. This corresponds on average to around 20% of the overall contamination coverage. However, the cleaning thereafter is minimal (Fig. 2); from 15 to 180 seconds after activation of the transducer, only an additional 3% coverage is removed.

When the water stream was deployed but with the ultrasound turned off, the 0.8 L min^{-1} water flow resulted in no cleaning effect over the 180 second exposure period. However, when the ultrasound is turned on, the same water flow produced good immediate cleaning efficacy, removing on average 50% of the contaminated area within 3 seconds of activation and restoring the area to background levels in 14 seconds (Fig. 2). As discussed in the previous section, binarisation of images of a rail-head without leaf-film is complicated by the presence of various dirt, grime and corrosion pits. In order to demonstrate the point at which a rail is restored to this baseline level, the mean level of this background noise is marked by a red line on Fig 2. Although cleaning rate decreases exponentially, further cleaning beyond baseline contamination levels is observed beyond 20 - 30 seconds of exposure, owing to the removal of some of the engrained dirt and grime. Progressive removal of the leaf-film is shown in Fig. 3.

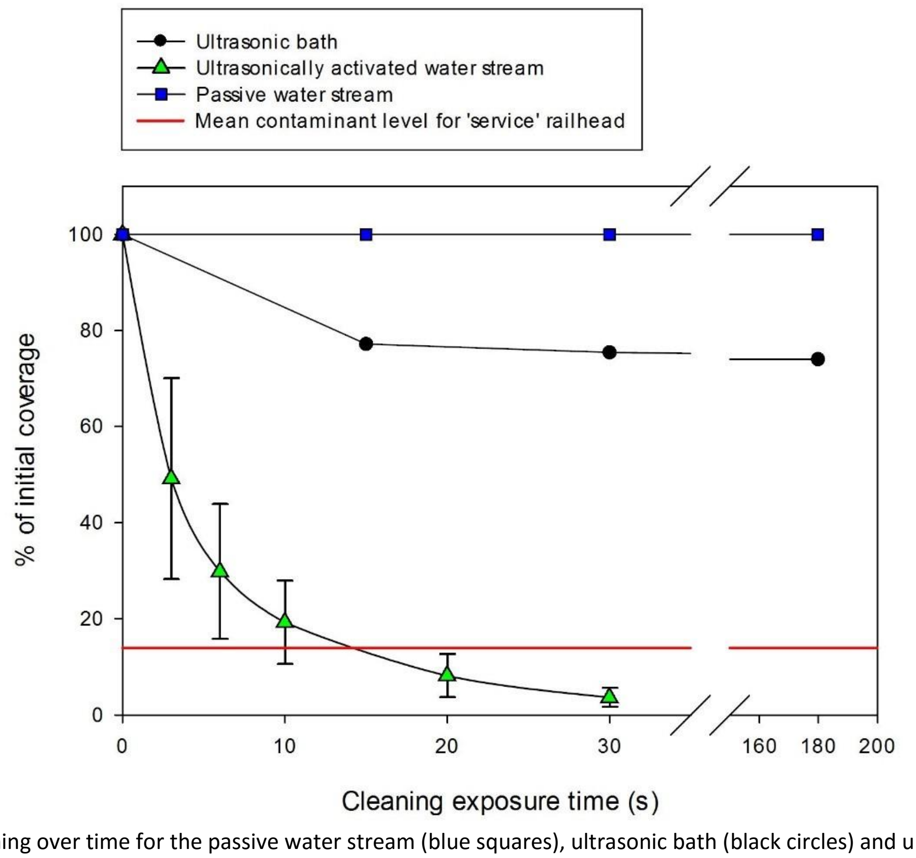


Figure 2. Cleaning over time for the passive water stream (blue squares), ultrasonic bath (black circles) and ultrasonically activated water stream (green triangles). The horizontal red line shows the mean baseline. Error bars are 1.6 standard deviations.

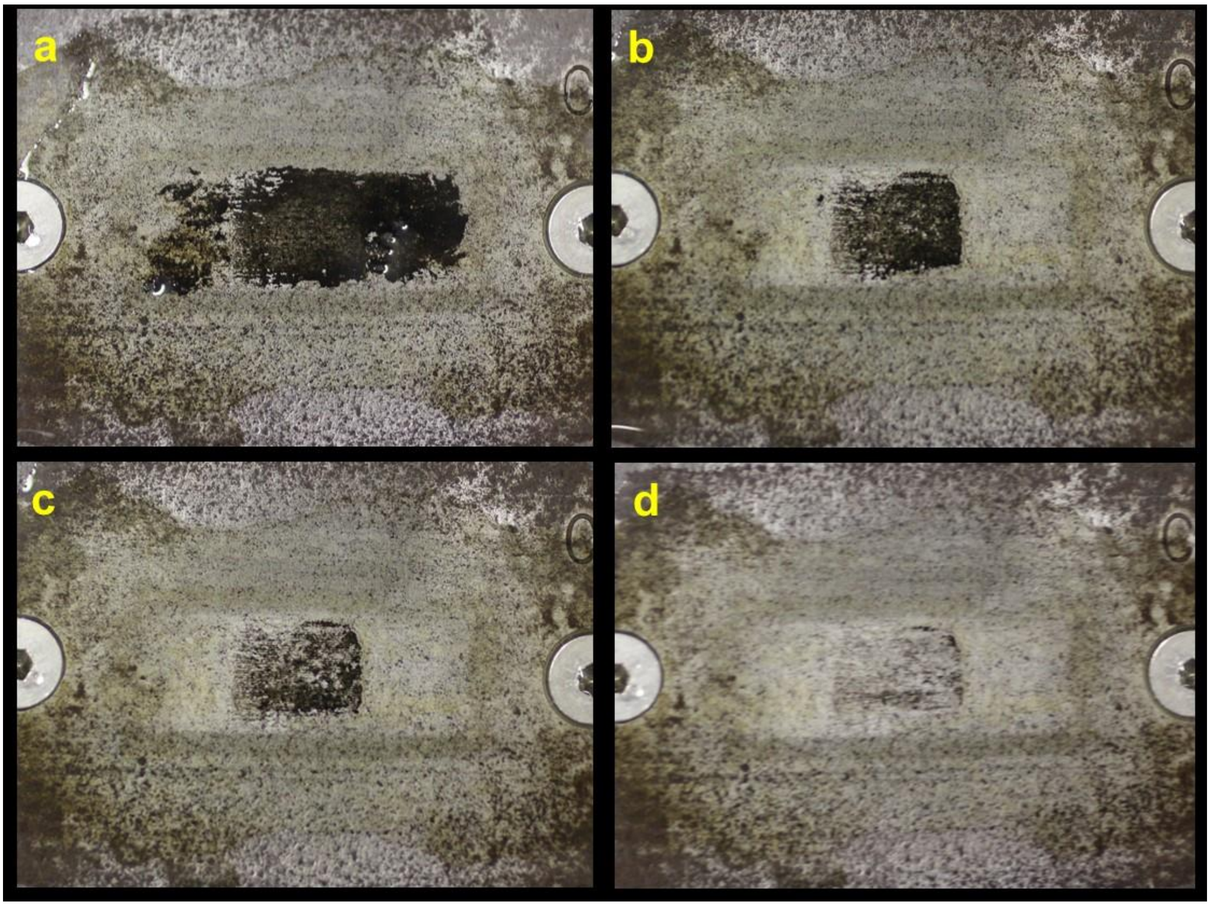


Figure 3: Removal of leaf-film during UAS exposure: a) pre-cleaning; b) after 3 s; c) after 6 s; d) after 20 s.

Optical profilometry analysis of partially cleaned surfaces demonstrates that visible removal of leaf-film corresponds to good cleaning performance, which was thorough even in the deep pits (Fig.4). In this image, the edge of a cleaned area is shown for contrast against a section remaining covered by leaf-film. In addition, on a separate sample, the organic matter in leaf-film was stained with propidium iodide and imaged using a DeltaVision Elite epifluorescence microscope in order to show coverage on the railhead steel, which has no inherent autofluorescence (Fig. 5). This demonstrates the uneven coverage and thickness of the leaf-film. The same area was measured after cleaning and fluorescent output had decreased to background levels, implying removal of the stained organic matter.

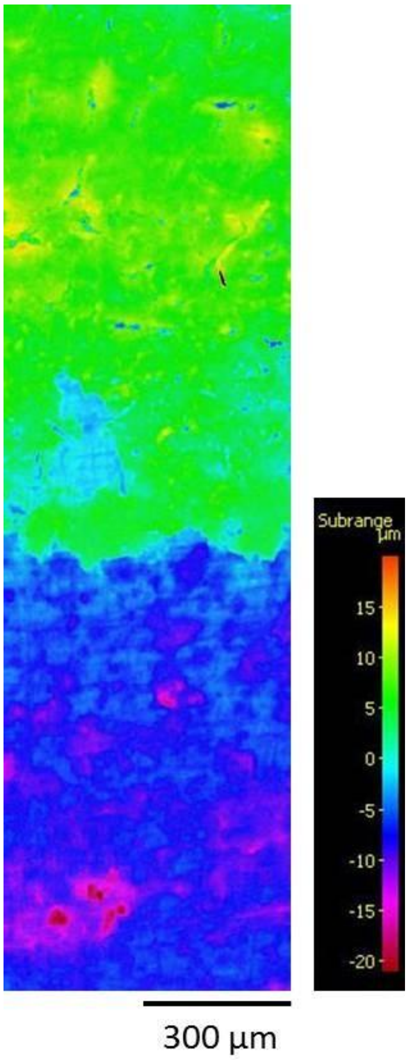
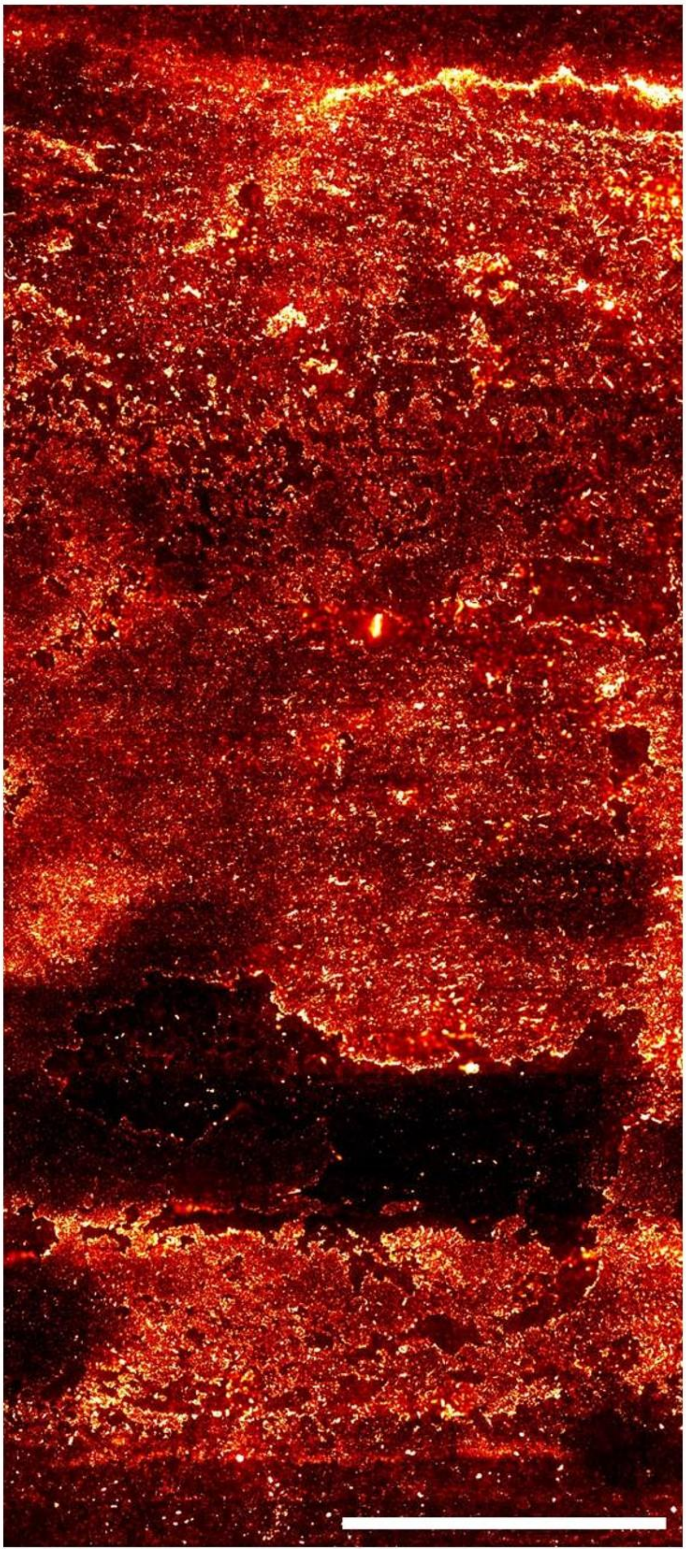


Figure 4: Height map showing leaf-film edge on railhead sample, demonstrating cleaned vs. non-cleaned area.

Figure 5: propidium iodide stained leaf film on railhead surface. Scale bar 2.5 mm.



Conclusions

A feasibility study was performed on the application of a novel portable ultrasonic cleaning device for rail cleaning. A comparison was made with an ultrasonic bath and solely water-based cleaning methods.

The first finding demonstrated by this study is that the StarStream device has been more effective than an ultrasonic cleaning bath at cleaning leaf contaminant from a railway track, even when using cold tap water without additives. The water stream was totally ineffectual; the ultrasonic bath exhibited low cleaning potential with loosely-adhered detritus being removed within the first 10 seconds – around 20% of the initial coverage - but with little cleaning occurring after that. The reason for this is that, whilst a well-defined ultrasonic field can be set up in an empty ultrasonic cleaning bath, that field will be disturbed when items are placed in it, strongly reflecting the ultrasonic field. In contrast, StarStream expects a reflecting target to be placed at the end of the stream, and so introduction of the target does not downgrade its performance. The target area was cleaned in 14 s by the UAS, whereas after 180 s the ultrasonic bath had only cleaned around 20% of contamination within the target area.

The second finding demonstrated by this study is the use of a portable UAS to clean railhead leaf-film contamination, with a mean cleaning rate in the order of 14.3 $mm^2 s^{-1}$ for a low water consumption of 0.8 L min^{-1}. In contrast, the initial cleaning rate achieved with the ultrasonic bath was in the order of 4 $mm^2 s^{-1}$ over the first 15 s; this decreased to 0.04 $mm^2 s^{-1}$ over the remaining 165 s.

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References

Birkin, P.R., Offin, D.G., Joseph, P.F. and Leighton, T.G. (2005) Cavitation, shock waves and the invasive nature of sonoelectrochemistry Journal of Physical Chemistry B, 109, 16997-17005.

Birkin, P.R., Offin, D.G. and Leighton, T.G. (2005) Experimental and theoretical characterisation of sonochemical cells. Part 2: Cell disruptors (ultrasonic horn) and cavity cluster collapse, Physical Chemistry - Chemical Physics, 7, 530-537.

Birkin, P.R., Offin, D.G., Vian, C.J.B. and Leighton, T.G. (2015) Electrochemical "bubble swarm" enhancement of ultrasonic surface cleaning. Physical Chemistry - Chemical Physics, 17(33), 21709-21715.

Birkin P.R., Offin D.G., Vian C.J.B., Howlin R.P., Dawson J.I., Secker T.J., Herve R.C., Stoodley P., Oreffo R.O.C., Keevil C.W. and Leighton T.G. (2015) An activated fluid stream - new techniques for cold water cleaning. Ultrasonics Sonochemistry, 29, 612-618.

GM/GN2642. Guidance on wheel/rail low adhesion measurement. Technical report, RSSB, 2008.

GM/GN2643. Guidance on wheel/rail low adhesion simulation. Technical report, RSSB, 2008.

Howlin R.P., Fabbri S.,Offin D.G., Symonds N., Kiang K.S., Knee R.J., Yoganantham D.C., Webb J.S., Birkin P.R., Leighton T.G., Stoodley P. (2015) Removal of dental biofilms with a novel ultrasonically-activated water stream. Journal of Dental Research, 94(9), 1303-1309.

Leighton, T.G., Pickworth, M.J.W., Walton, A.J. and Dendy, P.P. (1988) Studies of the cavitational effects of clinical ultrasound by sonoluminescence: correlation of sonoluminescence with the standing-wave pattern in an acoustic field produced by a therapeutic unit, Physics in Medicine and Biology, 33(11), 1239-1248

Leighton, T.G. (1994) The Acoustic Bubble, Academic Press, 640 pp.

Leighton, T.G., Birkin, P.R., Hodnett, M., Zeqiri, B., Power, J.F., Price, G.J., Mason, T., Plattes, M., Dezhkunov, N. and Coleman, A.J. (2005) Characterisation of measures of reference acoustic cavitation (COMORAC): An experimental feasibility trial. In A.A. Doinikov, ed. Bubble and Particle Dynamics in Acoustic Fields: Modern Trends and Applications, Research Signpost, Kerala, 37-94.

Leighton, T.G. (2007) What is ultrasound? Progress in Biophysics and Molecular Biology, 93(1-3), 3-83

Leighton, T. G., Birkin, P. R., and Offin, D. G. (2013) A new approach to ultrasonic cleaning. Proc. Int. Congr. Acoust., 19, 4pp.

Leighton, T.G. (2015) The acoustic bubble: Oceanic bubble acoustics and ultrasonic cleaning. Proceedings of Meetings on Acoustics (POMA), Acoustical Society of America, 24(1).
Maisonhaute, E., Prado, C., White, P. C. and R. G. Compton, R. G. (2002) Surface acoustic cavitation understood via nanosecond electrochemistry. Part III: Shear stress in ultrasonic cleaning. Ultrason. Sonochem., 9, 297–303.
Offin, D.G., Birkin, P.R. and Leighton, T.G. (2007) Electrodeposition of copper in the presence of an acoustically excited gas bubble, Electrochemistry Communications, 9(5), 1062-1068.
Offin, D.G., Birkin, P.R. and Leighton, T.G. (2014) An electrochemical and high-speed imaging study of micropore decontamination by acoustic bubble entrapment, Physical Chemistry - Chemical Physics, 16, 4982-4989.
Poole. W. (2007) T354: Characteristics of railhead leaf contamination summary report. Technical report, RSSB.
Rooney, J. A. (1970) Hemolysis near an ultrasonically pulsating gas bubble. Science, 169, 869–871.
Turangan, C.K., Jamaluddin, A.R., Ball, G.J. and Leighton, T.G. (2008) Free-Lagrange simulations of the expansion and jetting collapse of air bubbles in water, Journal of Fluid Mechanics, 598, 1-25.
Vian, C. J. B., Howlin, R. P., Dawson, J. I., Secker, T. J., Hervé, R. C., Stoodley, P., Oreffo, R. O. C., Keevil, C. W., and Leighton, T. G. (2015) Cold water cleaning of brain proteins, biofilm and bone – harnessing an ultrasonically activated stream. Physical Chemistry - Chemical Physics, 17, 10574.
Zhu, Y., Olofsson, U. and Nilsson, R. (2014) A field test study of leaf contamination on railhead surfaces, Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 228(1), 71-84.