Optics and Laser Technology 100 (2018) 133–138

Contents lists available at ScienceDirect

Optics and Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

Full length article

A comparative study on laser induced shock cleaning of radioactive contaminants in air and water

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A R T I C L E I N F O

Article history:
Received 17 June 2017
Received in revised form 22 September 2017
Accepted 7 October 2017

Keywords:
Pulsed laser
Shock
Decontamination
UO_2

A B S T R A C T

Efficient removal of Uranium-di-oxide (UO_2) particulates from stainless steel surface was effected by Nd-YAG laser induced plasma shock waves in air as well as in water environment. The propagation velocity of the generated shock wave was measured by employing the photo-acoustic probe deflection method. Monitoring of the alpha activity of the sample with a ZnS (Ag) scintillation detector before and after the laser exposure allowed the estimation of decontamination efficiency defined as the percentage removal of the initial activity. Experiments were carried out to study the effect of laser pulse energy, number of laser exposures, orientation of the sample, the separation between the substrate surface and the onset point of the shock wave on the de-contamination efficiency. The most optimised cleaning was found to occur when the laser beam impinged normally on the sample that was immersed in water and placed at a distance of ~0.7 mm from the laser focal spot. Analysis of the cleaned surface by optical microscopes established that laser induced shock cleaning in no way altered the surface property. The shock force generated in both air and water has been estimated theoretically and has been found to exceed the Van der Waal's binding force for spherical contaminant particulate.

1. Introduction

Laser assisted removal of particulate contamination, both loose and fixed, from material surface has major advantages over the conventional cleaning methods [1] and has found wide spread application in numerous areas of science and engineering [2–5]. In case of loose contamination that is adhered to the substrate surface predominantly by van der Waal's force, exposure to a laser pulse of appropriate wave length and fluence results in absorption of the incident energy by the substrate or the contaminants or both causing their expansion due to rapid rise in temperature. If the force induced by this thermal stress exceeds the adhesion force, the particulates are readily dislodged from the substrate [6]. However, direct exposure of the substrate to the intense laser beam may alter the property of the substrate surface that may be unacceptable in many applications. As an alternative to the thermal stress induced cleaning, laser shock cleaning has emerged as a promising technique that allows removal of loose particulates from the substrate surface without requiring it to be exposed directly to the laser beam. The shock wave is generated by focussing the laser beam at an appropriate distance above the surface to be cleaned in a gaseous or aqueous environment. The intense field in the vicinity of the focal spot causes ionization of the medium inducing a rapidly expanding plasma at the point of focus. This, in turn, creates a shock wave that moves outwardly at supersonic velocity [7]. If the force imparted on the particulate by this shock exceeds the van der Waal's binding force, it may result in expulsion of the particulate from the substrate surface.

In an earlier publication [8], we reported efficient cleaning of UO_2 contaminated glass samples by using shock waves generated in air by a nano-second duration pulsed YAG laser operating at 1064 nm wave length and capable of generating pulse of nano-second duration. Present work is an extension of our earlier work wherein we have compared the results of laser induced shock wave cleaning of UO_2 particulates off steel surface by shock waves generated in air and in water. The frequency doubled emission of an Nd-YAG laser electro-optically Q switched to yield pulses of 10 ns duration was made use of to effect the generation of shock. The second harmonic emission was chosen as against the fundamental used in our previous work [8], as it has better transmission in water [9]. Decontamination efficiency was estimated by counting the alpha activity of the samples before and after laser exposure using a ZnS(Ag) scintillation detector. The laser treated steel surface was analyzed for any possible surface damage by optical microscopy.

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https://doi.org/10.1016/j.optlastec.2017.10.005
0030-3992/

2. Experimental

In the first set of experiments the velocity of the shock waves as a function of laser energy at varying distances from the focal spot was estimated in air and in water by way of employing a red HeNe laser as probe and invoking the principle of beam deflection. The Nd-YAG laser was capable of delivering in the second harmonic a maximum of 800 mJ in the multi-mode over a beam area of ~ 1 cm^2 and pulse duration of 10 ns. The experimental scheme is shown in Fig. 1.

The Nd-YAG laser beam propagated in the horizontal plane and was focused with a lens of focal length 100 mm in air as well as in water in two different set ups. The water was kept inside a cuvette of dimension 100 mm × 100 mm × 50 mm. The energy of the laser pulse was measured using a pyro-electric Joule meter. The He-Ne beam, also in the horizontal plane but orthogonal to the Nd-YAG laser beam, was used to study the shock wave propagation by employing the beam deflection technique. The detail of the experimental procedure can be found in one of our earlier publication [8]. Shock wave velocity at different positions of the probe beam thus acquired allowed, in turn, the estimation of shock pressure in air (P_{sa}) and water (P_{sw}) respectively from the following Rankine-Hugoniot Eqs. (1) [10] and (2) [11].

$$\boldsymbol{P_{sa}} = \frac{P_1}{\gamma+1}\frac{2\gamma-(\gamma-1)M_S^{-2}}{M_S^{-2}} \quad (1)$$

$$\boldsymbol{P_{sw}} = C_1\rho V_{sw}\left[10^{\frac{V_{Sw}-V_w}{C_2}}-1\right]+P_0 \quad (2)$$

where $M_S = \frac{V_S}{V}$, V_S and V being respectively the velocity of shock and sound waves in air, V_{sw} and V_w are respectively the velocity of shock and sound waves in water. γ is the adiabatic coefficient of air (γ = 1.4), P_1 is the atmospheric pressure, ρ is the density of water, P_0 is the static pressure at water and C_1 and C_2 are empirical constants with values of 5190 m/s and 25,306 m/s respectively [11].

In the next set of experiments, the shock wave induced cleaning was effected to dislodge UO_2 particulates off steel substrate (Fig. 2). The cleaning efficiency was studied both in air and in water as a function of energy of the laser pulse for single and multiple exposures in steps of 0.1 mm placing the sample (1) horizontally (vertically down the focal point) and (2) vertically (sideways to the focal point). Relative positions of the sample with respect to the laser focal point for the above two cases are shown respectively in the traces a and b of Fig. 3.

Steel sheets, admeasuring 15 mm × 15 mm × 0.5 mm and cleaned in demineralised water and acetone to remove any superfluous contamination present on the surface, were used as the samples for simulation of UO_2 contamination. Minute quantity of UO_2 powder dispersed in a small volume of iso-propyl alcohol was sonicated in an ultrasonic bath for fifteen minutes. A droplet of the prepared suspension was deposited over a central spot of diameter 4–6 mm of the sample plate and was allowed to dry in air. The alpha activity of the samples so prepared was measured using a ZnS (Ag) scintillation detector. The sample plate was mounted on a precisely controllable 3-axis translational stage to facilitate its positioning either right beneath the focal point of the laser or sideways to the focal point and at a predetermined distance from it. Each sample was then exposed to several number of laser induced shocks with fixed laser pulse energy and fixed substrate-focal spot separation. After every exposure, the alpha activity of the sample was measured. In case of exposure in water environment, the samples were dried in an oven before activity measurement. The experiment was then repeated with varying laser pulse energies. For each measurement, a fresh sample was used. The same experiments were then repeated by changing the gap in steps of 0.1 mm.

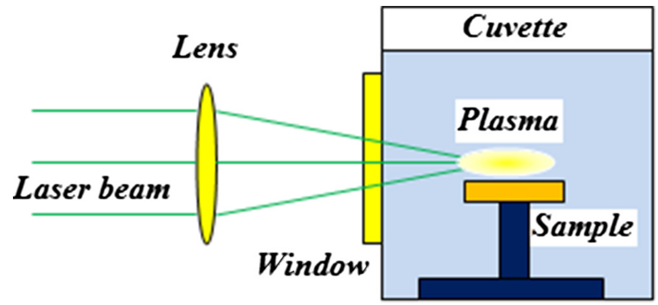

Fig. 2. Schematic of the laser shock cleaning setup in water.

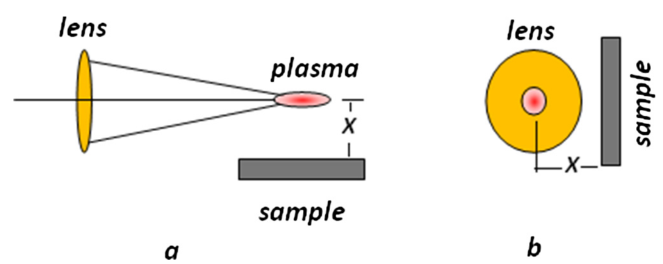

Fig. 3. Relative position of the samples wrt the laser focal spot. (a) Sample is placed horizontally beneath the focal point. (b) Sample is placed vertically sideways to the focal point. The direction of the laser beam is out from the paper.

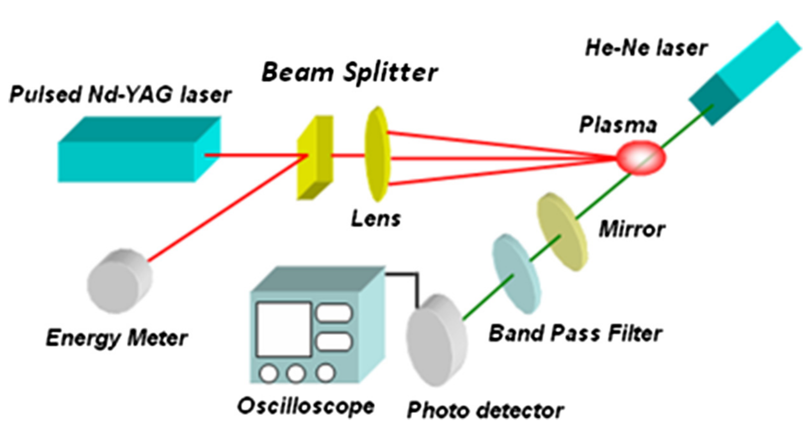

Fig. 1. Schematic of the experimental setup for determination of shock wave velocity in air.