Laser Irradiation of Microspheres and Shard-like Chalcogenide Glass Particles on a Silica Surface

A.M.Joyce*, D. M. Kane*, G. Elliott#, D Hewak#
*Department of Physics
Macquarie University ~ Sydney, NSW 2109, Australia
Email: debkane@physics.mq.edu.au
#Optoelectronics Research Centre, University of Southampton, Southampton SO17 1BJ, U.K.

***Abstract*— The effect of micro-particle shape on the laser – irradiation-field forward transmitted in a particle-on-a-surface system, and the resulting differences in processing, are reported.**

Keywords – micro-particle, laser/particle/surface interactions, micro-optics, laser processing, laser cleaning.

I. INTRODUCTION

The micro-sphere on a surface, irradiated by a pulsed laser, as shown in fig. 1, is a much studied laser/particle/surface system [1-7]. A range of interactions and related laser processing outcomes can be achieved in this system, depending on the materials of the microsphere and surface; the laser pulse energy, fluence and pulselength; processing geometry and laser beam focusing. Results range from: removing the microsphere from the surface, without any parallel optical damage (laser cleaning); cracking and "baking" some of the microsphere to the surface; nano-machining a hole in the surface using the near-field focused beam transmitted by the microsphere; and micro-scale contouring of the surface in rings and dashed rings around the point of contact between the microsphere and surface. While the micro-sphere-on-a-surface system is of significant technological importance in photonics and biomedical applications it is also the case that particles of different shapes occur in many real cleaning and processing applications. Irregular shaped particles have been the subject of many laser cleaning studies removing micron and submicron sized particles from substrates [1, 2]. All prior work has been performed using one type and form of particle on a substrate. In the current study a sample of mixed microspheres and shard-like particles of the same chalcogenide glass has been used. A sample before laser irradiation, containing both microspheres and crushed chalcogenide glass particles is shown in fig. 2. The laser cleaning and optical damage threshold fluences for the chalcogenide microspheres are found to be similar to those for smaller silica microspheres. However, the shards are significantly harder to remove and also exhibit more extreme laser induced optical damage at laser fluences above the range that gives damage free laser cleaning. Results of laser cleaning of both spherical and shard-like chalcogenide glass from silica substrates, and the optical damage geometry and topology caused on the substrate by the different shaped particles are reported.

INCIDENT LASER IRRADIATION

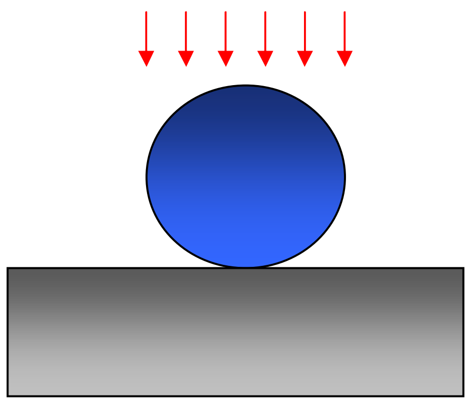

Figure 1: Microsphere-on-a-plane substrate subject to irradiation by a plane laser beam.

Figure 2: Image of chalcogenide spheres on a fused silica substrate imaged using a DIC optical microscope. Image size is 3.1 x 2.2 mm^2.

II. EXPERIMENTS AND RESULTS

The laser system used for the experiments is a GSI Lumonics PulseMaster PM-848 KrF excimer laser with a wavelength of 248 nm, pulse energy of 450 mJ at an average power of 80 W. The experiments are done using a single pulse. Figure 3 shows a schematic of the set-up used to clean the substrates. The laser beam passes through both an attenuator and a focusing lens to create a smaller beam and to increase the fluence. The computer controlled translation stage is used to precisely move the sample from in front of the microscope, where a before image is taken, to the path of the laser, and back to the microscope where an after image is taken. This method gives a highly accurate registration between particles in the before and after images. Typical image sizes are 1.4 x 1.0 mm^2 using a 250x magnification. The Attenuator used is an OPTEC AT4030 and the spherical lens has a focal length of 105 mm. During the laser cleaning process the particles that have been ejected from the surface of the substrate are removed from the site using a laminar flow of N_2 gas across the surface, this is to prevent redeposition.

The samples created for these experiments differ from those used in earlier studies in that the microspheres are much larger (20-120 microns in diameter chalcogenide spheres compared to 5 micron silica spheres) and at the present time no previous studies using such large spheres have been carried out. The particles are prepared by crushing the chalcogenide glass, which makes the micro-sized shard like particles. Dropping the microshards through an optical fibre-drawing tower forms the microspheres. During the fall the glass is heated above the melting point and forms spheres (the most perfect ones able to made on earth) by surface tension. A high number of the original shards, which are used in the production of the spheres, have been carried through to the contamination of the substrate. This serves a purpose to have both uniform (spheres) and non-uniform (shards) particulates in the same region of interest (ROI). The chalcogenide particulates are contained in a solution of isopropanol until they are needed, and are retrieved using a hypodermic needle and thus both the particulates and the isopropanol are deposited onto the substrate. The sample is given sufficient time for the isopropanol to evaporate, although there may be some residual solution left on the sample. Thus the method is 'damp' laser cleaning.

The substrate used is Fused Silica (UV7980) with dimensions 55 x 20 x 2 mm^3, with flatness better than $\lambda/2$. Fused Silica (FS) is known to be transparent between 0.17-0.37 μm [8] and has an absorption of 3.2 m^{-1} at the laser wavelength of 248 nm. This value may be higher since a hydrocarbon layer is present and acts as an absorption medium on the low absorbing silica. The damage threshold for fused silica has been calculated in previous experiments completed at MU [9] to be ~ 1.6 J/cm^2, which used 5 μm silica microspheres as the contaminant and consequently also as an absorption centre.

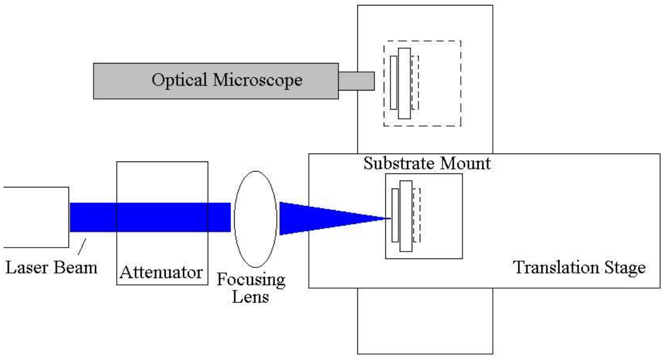

Figure 3: A schematic of the set-up used for the laser cleaning experiments.

An area containing, both spheres and shards present in the ROI is irradiated with a single laser pulse of a known fluence that is absorbed by both the particle and the substrate, causing an expansion of both media. The expansion of the substrate/particle is the primary method of detachment of the particle via overcoming of the van der Waal's adhesion force. Other forces contributing to the adhesion include electrostatic, capillary, and the image force from the particle. The laser cleaning efficiency is measured over a range of pulse fluences and the best fluence that removes the contaminants without damaging the surface optically is determined. The before and after images of the laser cleaning of chalcogenide glass particles on a silica surface are shown in Figure 4.

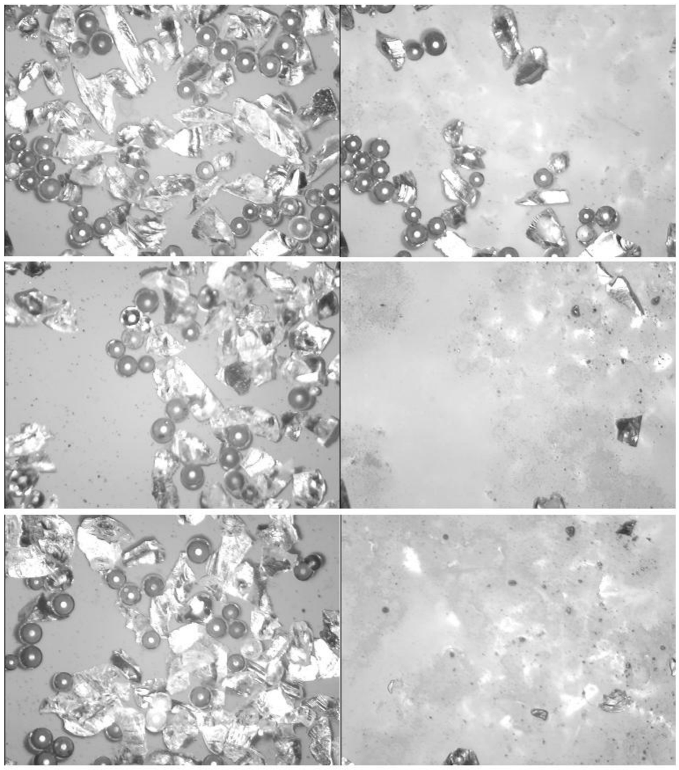

Figure 4: Before (left) and after (right) images of the laser cleaning experiments. Fluences for the images are top: 399 mJ/cm^2; middle: 1270 mJ/cm^2; bottom: 2429 mJ/cm^2. Image size is 1.38 x 1.04 mm^2.

Increasing the laser pulse fluence shows a change in the number of both the spheres and the shards that can be removed. At a low fluence (399 mJ/cm^2) a large amount of the shards (68%) are removed and only a small amount of the spheres (34%) are removed. As the fluence is increased (1270 mJ/cm^2) all of the spheres are removed and only a small amount of the shards are left. Increasing the fluence further (2429 mJ/cm^2) and past the expected damage threshold we see that removal of all the shards and spheres is achieved, although the surface of the substrate is left contaminated, not with the whole chalcogenide particulates, but with an unknown substance that needs further analysis to determine its composition.

The images can be used for calculation of the cleaning efficiency and the threshold fluence. The way this is done is to take the image and through several image processing steps, isolate the particles from the surface, and count the number of individual particles, of each type, present before and after the clean. The results for the laser cleaning of chalcogenide spheres and shards on fused silica are shown in Figure 5.

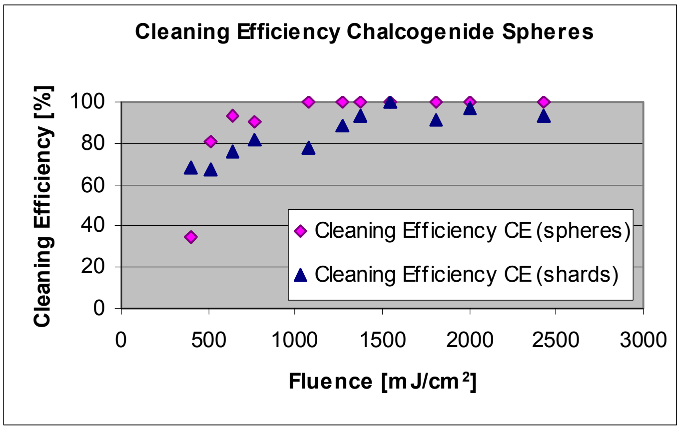

Figure 5: Cleaning Efficiency calculation for laser cleaning of chalcogenide spheres and shards from fused silica glass.

The difference in the cleaning efficiency (CE) of the spheres and the shards is quite evident and also from the before and after images acquired with an optical microscope. The data for the spheres have a much steeper rise to a maximum CE of 100% at approximately 1.1 J/cm^2, where all of the spherical particulates are removed, whereas the data for the shard particulates take a much steadier course to this maximum CE at approximately 1.6 J/cm^2.

The effect of increasing laser pulse fluence is not only observable in the before and after images but also in the sound of the cleaning process. A noticeable difference has been recorded using a video camera and microphone. There is noticeable change in the sound once the laser pulse fluence is raised above 1.1 J/cm^2, with a much louder noise heard when the laser pulse interacts with the substrate.

III. ANALYSIS AND DISCUSSION

Figure 4 showing the before and after images of the laser cleaning process show the particulates being removed but also leaves a question mark over the substance left on the substrate, and most noticeable, a change in the contrast of the silica in specific zones, evidenced by a white colouration. Over the whole data set the white colourations are more prevalent in the higher fluence irradiated samples, and always occur in the areas adjacent to a shard-like particulate. The contrast of the white colourations can be an indicator to the shape of the edge of the shard particle. A more defined or sharper edge of the original particle give a stronger white coloration. The texture of the shard is also important. The images from the optical microscopes used (figures 2 &4) show that the shards have a non-uniform texture, which may also give an indication of the shape of the side of the shard under inspection, while the spheres are assumed to spherical on the underside as well, the shape of the side of the shard in contact with the surface is unknown. The images show that the shards have a varying apparent normal incidence reflectivity over the surface, which arises due to different angled facets of the particle. Different levels of absorption and scatteing also result. From the before and after images the patches of white colouration (high forward reflectance) are found adjacent to both bright and dark edged (highly and lowly reflecting) shards. The most intense white colouration of the surface is found near the highly reflecting shards. Other colourations in the after images are of a grey colour and occur under the actual particulate, whether it is a sphere or a shard. Other debris is also present and is due to the sphere/shard breaking up as has been seen in other laser cleaning studies [9].

The values for the cleaning efficiency, as shown in fig. 5, show that as the fluence is increased the curve for the CE of the shards and the spheres cross over in the low fluence with the shards having a higher cleaning efficiency to begin with, but at a fluence of approximately 0.5 J/cm^2 the spheres are more efficiently removed. The prevalence of the areas of white colouration is also increased in the higher fluence samples suggesting that the laser light may be directed to the area to the sides of the shard where a possible localisation of the energy results in damage to the surface. Whether this damage to the surface is residue from the isopropanol or remnants of the shards being vaporized has yet to be determined. Under the sphere there is focusing of the light near the point of contact enhancing the energy directed to that point, but there is no observation of the types of optical damage seen with the smaller silica spheres. The higher absorption of the chalcogenide spheres does not allow enough light to transmit to the surface for these damage sites to arise.

As mentioned before the morphology of the underside of the shards are unknown whereas the spheres are well known. Knowing this we can say that the sphere has definitely only one patch of contact that lies directly at the centre of the bottom of the sphere. The shard has a number of points, patches and edges of contact or possibly a large contact point. The adhesion of the irregular shaped particle clearly varies from values well below the spheres to values well above.

IV. CONCLUSION

Laser cleaning of spherical and shard-like chalcogenide particles has been demonstrated, and shown that the morphology of the particulate has an effect not only on the cleaning efficiency but also on the optical transmission of the laser light. Spherical particles can be removed with similar fluences to that of the smaller silica microspheres. Shard-like particulates can also be removed, but not without damage to the surface. Material properties such as the varying reflectivity, multiple contact points/larger contact area, and the focusing at the sharp edges do not distribute the energy evenly and thus there is not a uniform heating, and expansion, of the shard, and the underlying substrate, leading to a failure in the removal of the shard or a breaking up of the shard. Knowing all of this would lead us the postulate that sharp edged particles are not a good candidate for laser cleaning.

ACKNOWLEDGMENT

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