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Laser Cleaning : Introduction and Applications

Jong-Myoung Lee[1, 2] and Ken Watkins[1]

[1] Laser Group, Department of Engineering, University of Liverpool
Brownlow Street, Liverpool L69 3GH, UK

[2] Manufacturing Technology Lab., Institute for Advanced Engineering
Yongin POBox 25, Kyunggi-Do, 449-800, Korea

ABSTRACT

Laser cleaning has begun to attract a considerable amount of interest recently as a new cleaning technique among scientists and engineers. The unique characteristics of laser cleaning are currently finding successful applications in industry, in medicine as well as in the world of art conservation. This paper takes an overview of the laser cleaning technique itself including basic principles and characteristics, and provides an account of current trends especially with regard to practical applications. Experience with its successful applications in various fields shows that laser cleaning may be about to emerge as a real alternative to conventional cleaning methods.

Keywords : laser cleaning, principles, characteristics, applications

1. Introduction

Surface contaminants such as oil, grease, various organic and inorganic compounds and undesirable particulates on the surface have been removed by various cleaning methods. Conventionally, organic solvents such as carbon fluorochloride (CFC) and trichloroethylene are employed to clean the surface. Although the solvents are effective in removal of most organic contaminants it is known to be harmful to the environment or pose hazards to workers. In particular, the use of CFC is being abandoned in many countries due to the depletion of the ozone layer. Many efforts have been made to find alternative methods such as plasma cleaning[1)], aqueous cleaning[2)] and CO_2 snow cleaning[3)]. Among them laser cleaning is growing in importance as a very feasible alternative for a novel, powerful and environment-friendly cleaning technique[4-6].

The origin of laser cleaning can be traced back to the 1960s when Arthur Schawlow, one of the pioneers of the laser, proposed a tool called the "laser eraser" which would be able to selectively vaporise strongly absorbing black pigment from strongly reflecting white paper. Then, Asmus and co-workers found the first practical application in 1973 in which a pulsed ruby laser could be used to remove black encrustations from a decaying marble sculpture without apparent alteration to the marble surface[7,8]. In the paper, they suggested the idea that the strongly absorbing black encrustation is removed by several pulses of laser radiation while the strongly reflecting white marble surface is left intact as the energy in the laser beam is simply reflected away (more detailed description can be found in the following section). Asmus believed that if this was indeed the case in practice then the use of laser radiation would lead to a major advancement in cleaning techniques i.e. a tool that could effectively detect a difference between layers of dirt and an object surface and respond accordingly. This was different from other techniques available at the time. Since then, many efforts have been carried out in order to investigate the cleaning mechanisms[9-16] and to find the practical applications in various fields[17-24].

2. Basic Principles of Laser Cleaning

One of the basic principles of laser cleaning is the photo-thermal effect as suggested by Asmus[8], which means heating and vaporisation of surface particles by direct laser absorption on target material. In many cases, the contamination layer has a large absorptance to the laser (although it depends on material properties, laser wavelength, etc). Assuming that material constants such as thermal diffusivity and thermal conductivity are the same for both the contaminant and the substrate, and only difference is surface absorptivity, then the principle of the removal of contaminant from the surface can be easily described as shown in Fig. 1.

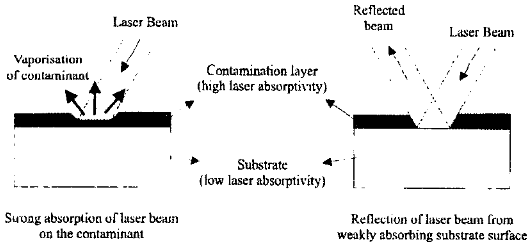


Fig. 1 Schematic illustration of basic principle of laser cleaning

The temperature of the contaminant having a relatively larger laser absorption is raised to high temperature very quickly, resulting in vaporisation. Once all of the contaminant has been removed, further laser pulses are simply reflected away from the substrate normally having a smaller laser absorptance. Since very little heat is induced by the poor absorptance in the substrate an intact surface is retained by the limited temperature rise. This is called "selective vaporisation process" or "self-limiting process", which is one of the most beneficial characteristics for laser cleaning since ablation of material from the surface of an object stops as soon as the contamination layer has been removed. The self-limiting cleaning can be observed in many cases, e.g. removal of strongly absorbing encrustation or paint from weakly absorbing white marble or metal substrate respectively.

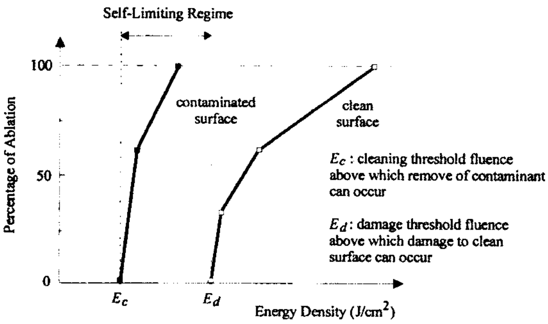


Fig. 2 Self-limiting nature: laser ablation thresholds for clean and contaminated surface

Fig. 2 shows the self-limiting nature graphically. If cleaning is carried out at an energy density below E_d but above E_c then the process will be self-limiting. The slope of the plots is a result of the inhomogeneous nature of the surface i.e. some areas of a surface are more easily cleaned than others. It is most important to realise that the cleaning threshold depends to some extent on the condition of the surface and cleaning is much more likely to be self-limiting if carried out at low energy density so that the most selective cleaning operates.

However it should be noted that laser cleaning is conducted not only by the photo-thermal effects but also by other effects such as photo-chemical effects[25-28] and mechanical effects[12,16,29-34] which are mainly dependent on laser parameters (laser wavelength, pulse length etc) and material properties. In particular, laser wavelength is believed to be one of the critical parameters for laser cleaning since the absorptivity of a material is strongly dependent on the wavelength of the incident radiation, ranging from ultraviolet to infrared[15,16]. Normally shorter wavelengths give higher energy coupling producing more efficient removal of a material while this provides more possibility of substrate damage due to its high laser absorption even on the substrate material (e.g. metals, semiconductors) as well as mechanical pressure induced by rapid evaporation and rapid expansion of the plasma plume. The proper selection of a laser with a particular wavelength (by considering the materials treated, such as contaminant and substrate) is therefore important for successful laser cleaning.

3. General Characteristics

Since laser cleaning is a physical process which is applied under conditions in which there is a strictly limited interaction with the substrate material, the procedure has distinct advantages over traditional cleaning methods based on chemical or mechanical action since it is a[12,16] :

- Physical process which ceases shortly after the laser pulse has ended
- Selective process which can be tuned for the removal of specific substances
- Non-contact process which can be automated and produces no contact wear
- Process that preserves surface relief
- Versatile process that most materials can

be removed by correct selection of operating condition

- Controllable process that a specific thickness of materials can be removed
- Sterilising process that surface organisms can be killed by laser induced high temperature
- Environmentally preferable process in which no large volumes of fluid waste products are produced and no environmentally damaging organic solvents are employed

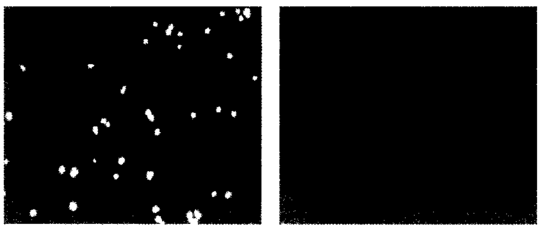
Although laser cleaning has many superior characteristics over conventional methods, it has its own disadvantages. For example, overexposure to the laser pulse may result in substrate damage (which is a crucial fault especially in art conservation) due to the high energy density of the beam whereas underexposure can leave residual contamination on the surface. It is therefore noted that a careful approach to laser treatment is needed during the process and in-process monitoring[16, 35-40] of the laser cleaning process is vital not only to achieve the sound cleaned surface without substrate damage but also to characterise the cleaning process.

4. Practical Applications

Recently successful applications of laser cleaning have been found in industry, in medicine and in the world of art conservation. Some practical applications are shown as follows, where the laser is used to advantage.

4.1 Particles removal from Si wafer

In the semiconductor industry, contamination control on Si wafer is one of the most crucial issues[41]. The shrinking dimensions and tolerances of devices require progressively the higher cleanliness levels on the surface. Normally the diameter of microscopic particles on the surface decreases with increasing density of chip devices and smaller particles are more difficult to remove due to the increasing adhesion force on the surface. The conventional cleaning techniques used in the semiconductor fabrication lines such as ultrasonic or megasonic cleaning and high pressure gas jet cleaning are inefficient in removing the micron or sub-micron particles as well as avoiding mechanical pressure-induced damage to delicate parts. These lead to significant yield loss and provide a limitation of further development of the chip technology. The laser cleaning technique has been demonstrated to be a promising new approach for effective removal of the very small particles on the surface, in which conventional cleaning techniques are inadequate for the removal[42-44].



(a) (b)

Fig. 3 SEM photographs on the surface of Si wafer before (a) and after (b) laser cleaning of particles (magnification (500)

Fig. 3 shows the SEM (scanning electron microscopy) photographs on the surface of Si wafer before and after laser cleaning. The particles on the surface are copper in the size of around a (m. The XeF excimer laser having the wavelength of 350 nm and pulse length of 8 nsec has been used. It is shown in Fig. 3 (b) that a well-cleaned surface without any damage is obtained by 10 pulses of the laser with a fluence of 0.34 J/cm^2.

4.2 Cleaning of printed circuit boards

The process of removing the oxide layers from copper printed circuit boards (PCB) is advantageous to the electronics industry in obtaining a good quality soldered joint with high bond strength by improving the surface wetability[39, 45]. The soldering features with and without cleaning the surface are illustrated in

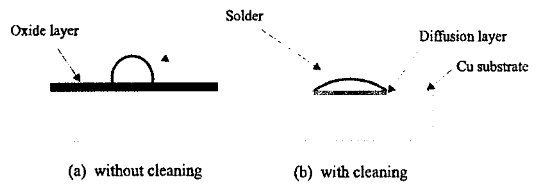


Fig. 4 Soldering features with and without cleaning the surface

Fig. 4. Normally, a large portion of the copper surface is composed of copper oxides. These copper oxide layers should be removed in order to achieve a good quality solder. Currently, acids in a flux are used to clean the oxide layer from the printed circuit boards. However the use of acids causes many problems including environmental problems with the flux which must be discarded after use. It is also difficult to use flux when it is necessary to solder complex structures or modules that cannot tolerate solvents and thermal stress. Substituting this traditional method with a laser process would be environmentally friendly without chemical waste and could easily be automated and incorporated into existing laser soldering processes[16, 39].

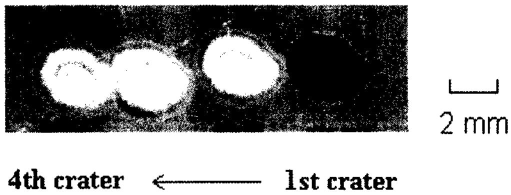


Fig. 5 Laser craters on the oxidised copper surface with multiple operation of laser irradiation

Fig. 5 shows laser craters on the oxidised copper surface with the sequence of the number of laser pulses. A Q-switched Nd:YAG laser with the wavelength of 1064 nm and pulse length of 10 nsec has been used in the laser fluence of 3.5 J/cm^2. The first crater at the right end is the crater produced by one laser pulse and the number of laser pulses increases one by one toward the left direction up to four laser pulses. It is shown that after one laser pulse the brown oxidised copper surface is changed to a dark black colour. This is caused by further oxidation of the Cu_2O to CuO due to laser induced high temperature[16]. Two laser pulses show a well-cleaned and shiny copper surface. Further laser pules did not significantly change the laser crater. It can be seen that successful laser removal of copper oxides from copper is carried out using the multiple pulse operation of the Q-switched Nd:YAG laser.

4.3 Cleaning of moulds in tyre -manufacturing

The method for cleaning tire moulds

traditionally involves scouring the moulds with glass beads applied at high pressure. Moulds for high-end tires with details on the side-walls have to be cleaned every two or three weeks. This technique is expensive, messy and can erode the mould's surface, which eventually results in low quality outputs and requires replacement of the expensive moulds.

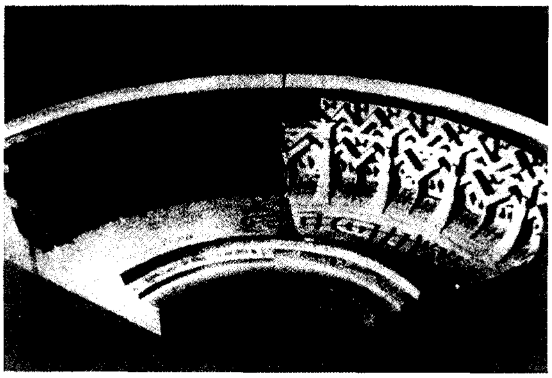
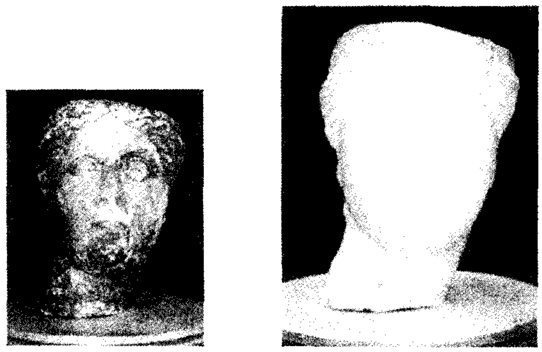


Fig. 6 Surface morphology of tyre mould before laser cleaning (left side) and after laser cleaning (right side)[46)]

Fig. 6 shows a well-cleaned area in the right side of the mould by excimer or Nd : YAG laser irradiation, which removes the surface contaminants successfully and causes no damage to the underlying mould surface[46)] (which is a licensed process). In this case, the pulsed laser lifts contaminants from a mould and a pure inert gas then sweeps the contaminants from a trap. It was also reported that CO_2 laser was successfully applied to remove tyre compounds clogged in microvents of the mould, which is conventionally cleaned using a high speed drill in manual[47)]. As a result, the laser cleaning technique for tire-manufacturing can dramatically cut production costs, reduce environmental impacts and perform cleaning without degrading the tire moulds.

4.4 Cleaning of stone for art conservation

The formation of unsightly and damaging black encrustation on stone monuments due to interaction with atmospheric pollution has become a familiar problem. Traditional cleaning techniques such as particle abrasion and liquid jets have often proved successful in restoring the outer appearance of a sculpture. However, by their very nature these techniques damage the underlying stone and often result in the loss of fine details from a sculpture. Recently, it has been found that laser process has given promising results in which polluted layers are removed selectively from the sculpture without damage to the underlying stone[8, 28, 48, 49)] with the added advantage of sterilising the surface during the high temperature process.



(a) (b)

Fig. 7 Laser cleaning of a Greco-Roman marble head which was excavated in Shropshire, England: (a) initial appearance covered in soil and whitewash, (b) restored appearance after laser cleaning[50)]

Fig. 7 shows one of the examples of laser applications in the cleaning of a marble sculpture[50]. A Q-switched Nd : YAG laser with a fundamental wavelength of 1064 nm has been used in this work. Contaminants such as soil and whitewash on the surface have successfully been removed by the laser treatment without damaging the substrate marble. However, this has to be done in a very controlled manner since laser induced underlying substrate damage is a fatal fault in art conservation. In addition, the growing number of uses of laser in art conservation include the removal of corrosion products from bronze, encrustation from stained glass, fungi from leather and vellum, and recovering original paintings from overpaintings etc[51-53].

5. Conclusions

As seen in this paper, laser cleaning has demonstrated outstanding capabilities for the removal of diverse contaminants on the surfaces. Due to its unique characteristics as a selective, precise, controllable and environment-friendly process, the laser cleaning technique has a huge potential for a wide range of applications both in industry and in the world of art conservation. It is also seen from the examples of its application that laser cleaning provides many advantages over conventional cleaning techniques based on wet chemical or mechanical actions.

It is believed that this new processing technique is on the threshold of a widespread diffusion into industry. More understanding and investigation of laser technology, laser-matter interactions during the process and a realisation of the processing system may provide a promise for its success.

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