Laser Cleaning of Metal Surfaces: A Review

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Abstract: Metal surface cleaning is becoming increasingly significant in modern manufacturing. Using processes that are safe, efficient, economic and environmentally safe is most important. Laser cleaning is such a process. This paper covers the characteristics of laser cleaning operations, kinds of lasers used in cleaning metal surfaces and the applications of laser cleaning in industry.

Keywords: surface cleaning, descaling, carbon dioxide, abrasive, ultra-violet, environmentally friendly, non-contact.

1. Introduction

Light amplification by stimulated emission of radiation (laser) is a coherent and monochromatic source of electromagnetic radiation that can propagate in a straight line with negligible divergence. (1)

Nowadays lasers are used across the manufacturing sectors for various material processing applications, from nanofabrication to surface cleaning. Laser cleaning is a technique that allows controlled removal of surface contaminants from the bulk of a material. One of the major advantages of using a laser as a tool for material processing is its ability to precisely control the energy deposition and hence the material removal process, making it an equipment of choice for cleaning or contaminant removal process. (2)

This method is non-contact as well as non-destructive. Laser cleaning doesn't need any abrasive or chemical media. The suitable laser type and optimum parameters are different for each application. (3)

At laser cleaning low levels of radiation intensity are used, so contaminations removal can be realized not only by means of evaporation, but also in the solid phase, in this case thermal influence on the substrate is very small. Possibility of variation of laser output parameters on a large scale allows one to choose the generation regime particularly for removal of every type of the surface contamination. Laser cleaning also has another advantages, such as remotability , absence of mechanical damage of the surface, high productivity.
There are two types of laser cleaning: dry cleaning and steam one, which are based on the pulse laser heating of solid surface (dry) and in presence of liquid layer on it, correspondingly. By increasing laser pulse energy the method of dry cleaning turns into evaporative cleaning. The technique of dry cleaning is simple, but its effectiveness is less,

than for steam cleaning, and required laser intensity is higher (for nanosecond pulses). Power thresholds of the steam cleaning are in 2 or 3 times higher than for dry cleaning. Sometimes dry laser cleaning can result in local damage of the surface. If the mentioned shortcomings of dry laser cleaning turn out to be significant, steam laser cleaning has to be used. (4)

2. How does laser work

It's probably a bit blurry as to what exactly a laser does when removing rust. Here are the important facts to know regarding this new application of laser technology.

1. All materials have an ablation threshold

Laser ablation occurs when a layer of a material or a material which is deposited on a given surface is removed with the aid of a laser beam. This is actually the process behind laser rust removal on steel and other materials, Molecular bonds in the dust or rust layer are broken and ejected from the substrate. In less technical terms, you can imagine that the layer to be removed is simply vaporized by the laser beam.

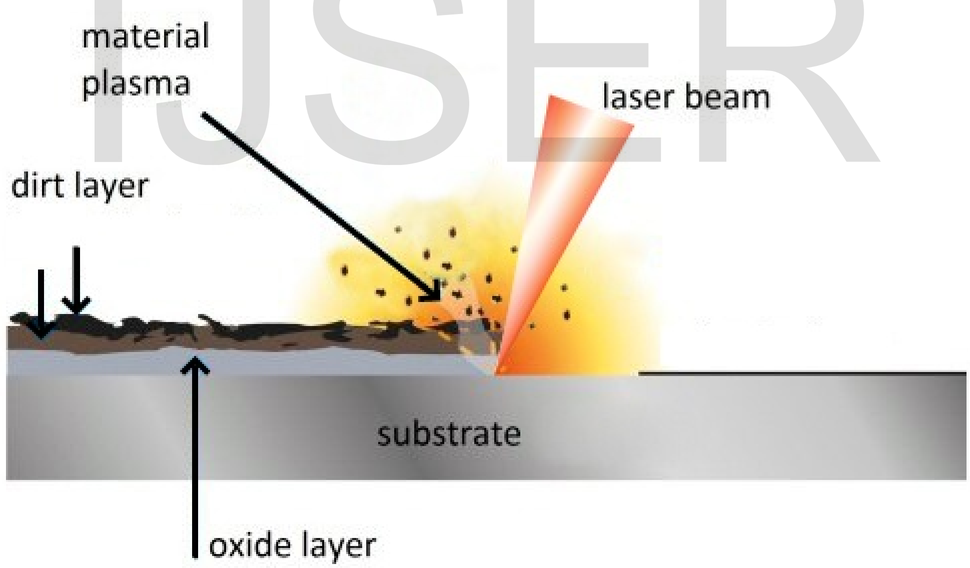

fig. 1 - Laser Ablation

A simple way to get a grasp of the importance of the laser threshold is to relate the concept of the laser threshold to one of throwing a ball over a wall. If you don't throw the ball higher than the wall, it will obviously never make it over. Even if you repeat throwing the ball a thousand times, the ball will always fail to make it to the other side. It's the same thing with laser derusting. You can shoot the laser beam a thousand times and as long as

the energy is below the threshold necessary to impact the particular material you are working with, everything will remain the same.

Now, since every material has different properties and thus different molecular bonds; there is a specific ablation threshold for each material. Therefore, to successfully remove a layer from a given material, it is important to make sure the energy transferred by the laser beam is above the ablation threshold of that particular material.

2. It is possible to remove a material in a highly selective way

Let's continue with our analogy. Imagine there was a second, higher wall behind the first and that a ball is thrown with just enough energy to make it over the first wall, but the ball does not have enough energy to make it over the second wall. It will then bounce off the second wall and fall in between the two walls. Once again, no matter how many times you throw the ball, you will always get the same result. You will make it past the first wall, but not the second.

Since there is an ablation threshold for each material, it is possible to discriminate between two or more materials when trying to remove an undesired layer from an object. Given a sufficiently large ablation threshold difference between the materials, it is possible to select one material to be removed (the one with the lower ablation threshold), leaving the other material untouched.

For example, the rust ablation threshold is much lower than the threshold for common metals such as aluminum or steel. The same goes for paint and oil thresholds compared to the thresholds for different metals. It is this vast gap between the two values that effectively allows rust to be completely vaporized without any risk of damage to the steel underneath. There's just not enough energy for damage to happen.

3. Strong and short power burst means faster removal

You can think of laser ablation as similar to a stone carver with a hammer and chisel, trying to carve a stone. You can use a small hammer, and do many little hits on your chisel. Or you could just as well use a bigger hammer to leverage more power, hence reducing the required number of hits and increasing the removal speed. The idea is the same for laser cleaning, except that you only want to remove a layer of material: the contaminant.

There are different methods available to remove any given layer. Either the laser beam is a continuous stream of light or it is pulsed at a given duty cycle. Even if the end result is pretty much the same; the speed of the process is quite different depending on the methodology chosen.

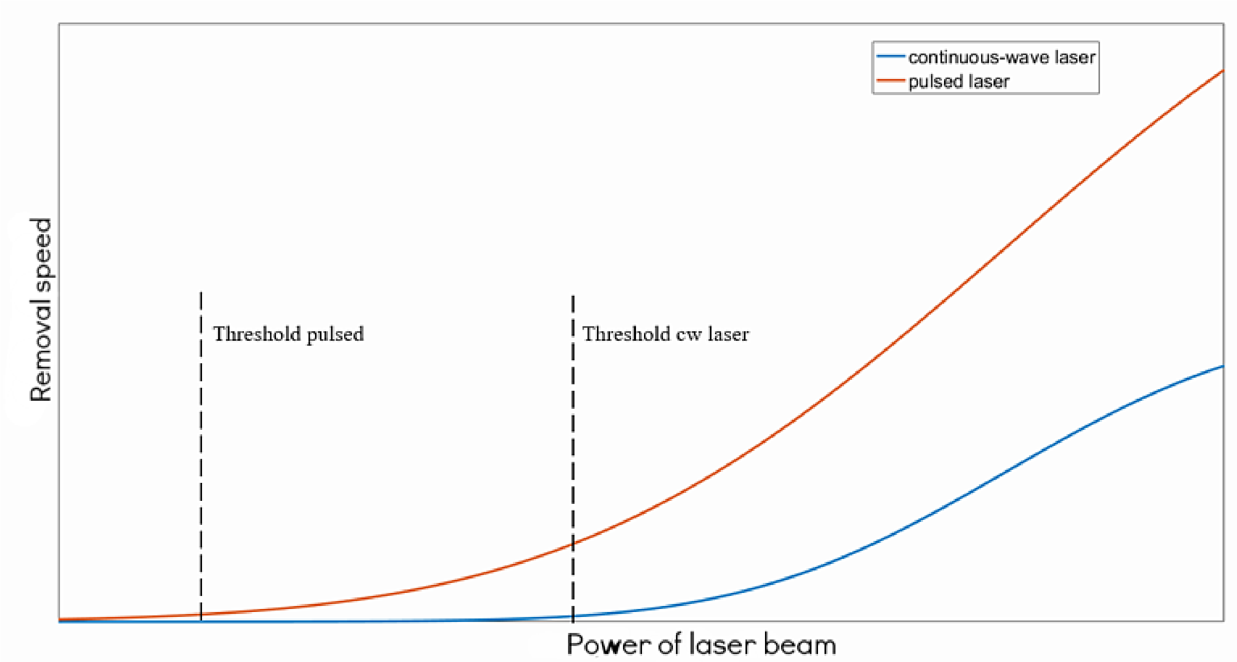

Fig. 2 - Graph: Relation of Removal Speed to Power of Laser Beam.

For a given surface area, putting the same energy in a much shorter pulse increases the power. It's like using the bigger hammer. The pulsed laser methodology is more efficient and provide a faster removal speed than the continuous beam. While the pulsed laser beam do the cleaning faster, it also ensures that the underlying material (typically a metal) does not heat too much. See the graph above for an illustration of the differences between both processes.

4. It is consumable-free and environmentally friendly

As this method only uses a laser beam to vaporize the layer to be removed, there are literally no consumables with this cleaning technology. This is the beauty of a laser, which only needs a power plug to be set and ready to go.

On top of this, as no solvents or other chemical products are used, laser ablation is one of the safest solutions available when it comes to rust removal. Hence, there's no chemical waste to take care of. Also, there is no danger for employees while working with the laser machine as these machines are designed to meet safety standards. Employees won't need cumbersome personal protective gear and won't have to handle those pesky chemicals. Win-win.

5. Laser cleaning is of interest for various industrial processes

Removing the burnt rubber residue from tire molds; giving a new life to old pipelines; cleaning pipes in nuclear power plants; and even larger projects such as removing paint from a rusty bridge are all projects that can benefit from laser cleaning technology. Thus, this technology can be used in a lot of different fields of application; the only constraint

being the ability to discriminate ablation thresholds between the material to be removed and the one to be protected. (5)

3. Kinds of lasers used in industry

Excimer lasers operating at ultra-violet (uv) wavelengths are successful at processing many organic polymers and are effective in laser cleaning but the relatively high absorptivity of metals at uv wavelengths is a problem where heating or melting effects upon the metal substrate have to be considered. A recent novel and successful application of laser cleaning utilizing a Nd: YAG (Neodymium: Yttrium Aluminum Garnet) laser has been to clean leaves from railway tracks. Although lasers can be used to harden metals by introducing compressive surface stresses, this does not occur under the typical operating conditions used for laser cleaning. Other applications of laser cleaning include tyre mold refurbishment, although little has been published of relevance to larger industrial scale cleaning of metal molds and, in particular, to the removal of cured resin from such tooling. Robotically controlled solid-state lasers used in tyre mold cleaning can clean approximately one square meter of surface area within 45 to 60 minutes, representing a very significant improvement on conventional abrasive cleaning methods.

Laser cleaning of large surface areas presently utilizes TEA (Transversely Excited Atmosphere) CO_2 lasers possessing multi-kilowatts energy outputs. These are pulsed lasers that can clean large areas quickly. Carbon dioxide lasers are an obvious choice since the laser output wavelength of 10.6 micrometers (μm) couples very effectively to the molecular vibrational modes of many organic materials causing them to heat up and degrade. An organic resin should, therefore, readily absorb energy at this wavelength. Metal substrates are also highly reflective to this laser wavelength with the consequence that the cleaning process is self-limiting with only the organic contaminant being removed. TEA CO_2 lasers require separate gas supplies to operate. Sealed radio frequency excited CO_2 lasers are an alternative that do not require gas supplies and their reduced physical size makes them more suitable for robotic mounting. These systems though are not as powerful as TEA CO_2 lasers and the intended market for them is biased towards materials processing rather than cleaning applications. Shorter wavelength lasers such the Nd:YAG solid state laser are also available for cleaning and find greatest application in art restoration work but the reflectivity of metals falls off at shorter wavelengths so that there is a greater chance that some substrate damage may occur when they are used to remove coatings from metals. Most applications of CO_2 lasers utilize CNC tables to move the work-piece requiring cleaning with the laser being either static or mounted on a robot arm; with appropriate control over the arm the laser is scanned over the area to be cleaned. Where the cleaning of very large molding tools is considered, the work piece cannot be moved and some form of automation is required to scan the laser over the area to be cleaned. The physical size of a TEA CO_2 laser would suggest that this option would be costly to implement and not very flexible. Aside from the cost issues involved in realizing an industrial scale laser cleaning solution with CO_2 lasers, the technology has some other disadvantages. At present, there exist few materials that will transmit the 10.6 μm wavelength significant absorption. The main exceptions are zinc selenite or germanium and focusing optics have to be produced from these rather exotic materials. Highly polished mirrors made from gold or copper can

also be used because of the high reflectivity of metals at 10.6 µm. Unlike CO_2 lasers used for cutting and welding processes, where optics focus the laser light down to very small spot sizes, laser cleaning requires defocused beams covering an area of a few square centimeters. Ideally, the energy distribution across such beams should be uniform but this is difficult to achieve because of the way high power CO_2 lasers are designed. Measuring laser energy densities (or fluences) for intense lasers poses experimental problems since conventional power meters used for most other laser power measurements are very easily damaged by high-energy pulses and very expensive to replace. Such measurements are desirable to optimize any cleaning process but are difficult to make and estimated measurement errors of ±10% or more are common. Other critical factors are the pulse duration and repetition rate. A minimum (or threshold) intensity is required to thermally ablate any contaminant layer and this is a function of the material composition. Despite a greater propensity to cause thermal damage on metal substrates due to the reduced reflectivity, the use of Nd:YAG lasers, operating at an output wavelength of 1.06 µm, offers some distinct advantages. Glass fiber optic beam delivery from the laser source to the work piece is possible because there is very little absorption by the glass at this wavelength. This greatly enhances the flexibility of the cleaning process since a skilled operator can now man oeuvre a hand held laser cleaning head over the area to be cleaned and if necessary simply increase the fluence to remove stubborn contamination. The use of a solid-state laser also makes the laser inherently more reliable and free from operating faults. The technology of these lasers is well developed. Unlike TEA CO2 lasers, which are physically bulky systems requiring gas and three phase electrical power supplies the size of Nd:YAG systems has been steadily reduced and current small footprint units are marketed. These advantages are made at the sacrifice of cleaning rates which are slower than using CO_2 lasers but still competitive with other non-laser cleaning methods. In most other respects Nd:YAG lasers offer the most cost effective laser cleaning solution. (6)

4. Applications for laser cleaning

1. Surface profiling and rust removal in steel fabrication: Conventional rust removal and descaling operations involve the use of physical methods such as blasting, polishing, scraping devices, extra blows, and wire brushes. Chemical methods such as alkali descaling and acid descaling (pickling) can also be used for scale removal. However, these methods are very abrasive and result in environmental pollution and damage to the substrate metal. To avoid these disadvantages, laser cleaning has become the preferred method for rust removal and descaling operations. The rust/scale is removed by directing a laser beam with high peak power and repetition rates on the rusted layer. The laser must be fired in short pulses to avoid damage to the substrate being worked on. The rust rapidly absorbs the energy of the laser beam, resulting in increased temperature levels. Once the temperature is sufficiently high, the rust melts and eventually vaporizes. Using pulsed fiber lasers is the preferred option since it provides greater control over power, wavelength, and pulse duration, allowing the rust/ scale to vaporize without any damage to the underlying material. The laser cleaning process can also be applied to surface profiling. Before protective coatings can be applied to fabricated steel parts for preservation and protection from corrosive action, their surfaces must be clean and free from all contaminants.

2. Anode assembly cleaning: The aluminum smelting industry uses carbon blocks as "sacrificial" anodes in the production of primary aluminum. The quality of the anode has an impact on the environmental, economic, and technological aspects of aluminum production.

A small percentage of cell power is devoted to overcoming the electrical resistance of prebaked anode. The presence of dirt and other contaminants will increase the anode's electrical resistance, resulting in the consumption of more cell power. The presence of contaminants also reduces the lifespan of the anode by increasing its rate of consumption during the smelting process. From the standpoint of efficiency, it is necessary to clean and remove all surface contaminants from anode assemblies before they are used in aluminum smelting operations. In addition, anode assemblies are valuable tools that can be reused, but only after executing a thorough and careful treatment of its main components—under specific conditions. Laser cleaning meets the specific conditions under which anode assemblies can be treated for reuse.

3. Adhesive bonding preparation for metals: To increase process stability, surface adhesion, and better seam quality, the surface of the metallic materials to be joined must be prepared before the application of welding and other joining techniques. Laser cleaning is suitable for adhesive bonding preparation since it removes oxides and other contaminants such as grease and oxides that reduce the strength of adhesive bonds. It is particularly suitable for applications involving curved or flat surfaces or parts with certain limitations for highly complex 3D geometries.

4. Pretreatment for brazing and welding: Laser cleaning has also proven effective in pretreatment applications for welding and brazing. Before aluminum and steel materials are used for welding purposes in shipbuilding, precision tool manufacturing, automotive, and other related industries, their surfaces must first be prepared. Laser weld preparation is one of the many applications of laser cleaning and helps to remove ferrous and nonferrous metals, lubricants, and other contaminants from metal and aluminum surfaces in preparation for high-quality welds. It also ensures smooth and pore-free brazed seams. Apart from welding and brazing preparation, lasers can also be used to remove weld residues such as residual flux and oxide materials as well as thermal stains from finished weld joints. This cleaning method is particularly beneficial for stainless steel parts since laser light suspends grain boundaries, ensuring that weld seams are passivated—thus increasing corrosion resistance.

5. Partial de-coating:. Laser cleaning is particularly effective in applications that require the partial removal of paint or coatings from finished surfaces. It can be used on virtually all surface types, whether chemically anodized, oxidized, or organic. Laser cleaning can be used to de-coat solar panels and remove paint in the automotive and aerospace industries while maintaining the integrity of the primer substance .In de-coating applications, fiber lasers are the preferred option. They obviate the need for masking by precisely removing the layer of coating in the specified area, thus eliminating some of the challenges inherent in partial de-coating applications.

6. Selective paint removal: Selective paint removal represents one of the many applications of laser cleaning. In the automobile and aerospace industry, it is sometimes necessary to remove the top layer of paint while maintaining the primer. This is often the case when the

top weathered coatings on vehicles need to be thoroughly removed before the application of a new paint finish. Since the top layer of paint is physically and chemically different from the underlying primer, the power and frequency of the laser can be set to a frequency that only removes the top layer of paint. The primer remains intact since the laser has no mechanical, chemical or thermal effect on it. This ensures the maintenance of the primer's corrosion resistance ability. When bare metal-to-metal contact is required for electrical continuity between parts, the laser cleaning process is preferred since it saves time and materials while improving the quality of the finished surfaces. (7)

7. Dirt removal from metal mold surfaces: Mold surface cleaning is a process where major maintenance bottlenecks occur as molds are usually pulled faster than they can be cleaned and made production ready. Cleaning mold plates and re-tooling are usually more tedious, time-consuming, and labor intensive than any of the other repair stages (disassembly, troubleshooting, or reassembly) combined . A new approach is needed to realize a major reduction in the time required to clean molds, to maximize tooling life, to make cleaning more systematic, consistent and predictable. Laser cleaning technology for the mold surfaces would, therefore, be a more suitable technology for this purpose. (8)

5. Summary

Unconventional laser cleaning methods increases the quality and effectiveness of cleaning of metal surfaces. Proper ablation conditions allow to assess the higher efficiency and selectivity of laser cleaning with respect to traditional mechanical or chemical treatment. It is relatively easy and it is environmentally safe.

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