Laser-Aided Manufacturing: Atom to Application

Jyoti Mazumder

1 Introduction

Laser as a pure form of light offers new form of industrial energy that is being harnessed for a multitude of manufacturing processes. Each form of new energy ushered a new era [1]. Mechanical energy used via tools started the civilizations we know it now. Steam energy started the Industrial Revolution. Table 1 lists different forms of energy and its influence on society.

Lasers are now used for atomic level isotope separation [2] in Atomic Energy and zapping of eyes for corrective eye surgery [3]. Lasers first came as imagination by H. G. Wells in his story "War of the World" serialized in the Pearson magazine in U.K. in 1897. Science of LASER came later. Laser is an acronym for "Light Amplification by Stimulated Emission of Radiation." Einstein [4] first observed the phenomenon of "Stimulated Emissions" in 1916 while studying the interaction of an atom with electromagnetic field.

The concept of generation of laser light includes three main components, i.e., optical cavity, electromagnetic energy for amplification, and atomic media. It was first published by Schawlow and Townes [5]. Theodore Maiman made the first laser operate on May 16, 1960 at the Hughes Research Laboratory in California, by shining a high-power flash lamp on a ruby rod with silver-coated surfaces. In the beginning, CO_2 laser [6] invented by C. K. N. Patel provided high power suitable for manufacturing use. Later on, solid-state lasers were adapted for high power. Now lasers with dimers as medium with ultraviolet wavelength (~192 nm) to far-infrared CO_2 (10.6 μm) are being employed for various manufacturing applications [3]. Lasers are now enjoying revenues exceeding $14 billion (see Fig. 1).

The market segment for the lasers is shown in Fig. 2 [7]. Material processing is the largest segment of laser application. Auto industry has embraced lasers since 1978 in

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U. S. Dixit and S. K. Dwivedy (eds.), *Mechanical Sciences*,
https://doi.org/10.1007/978-981-15-5712-5_11

Table 1 Laser as a new form of industrial energy (*Source* W. M. Steen, Emeritus Professor University of Liverpool)

Form of energy	Usage	Influence on society
Mechanical energy	Tools	Start of civilization
Chemical energy	Furnaces	Iron and bronze ages
Wind energy	Windmills, sailing ships	Start of industry, international trade
Water energy	Water wheels	Industrialization
Steam energy	Steam energy	Industrial revolution
Electrical energy	Dynamo	Distributed power, radio, telephone, motors
Oil/petrol	Compact power	Transport revolution
Nuclear power	Generators, bombs	Unlimited energy changed world politics
Optical energy	Laser	CDs, printers, bar code, communication +++

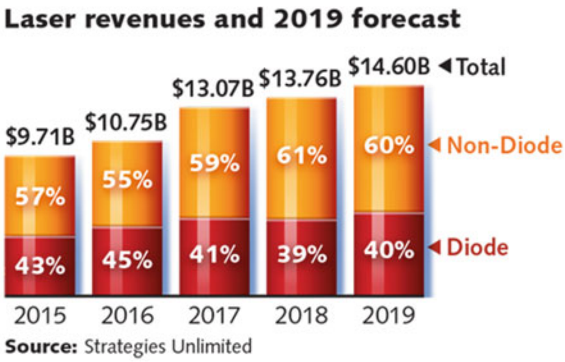


Fig. 1 Global laser market [7]

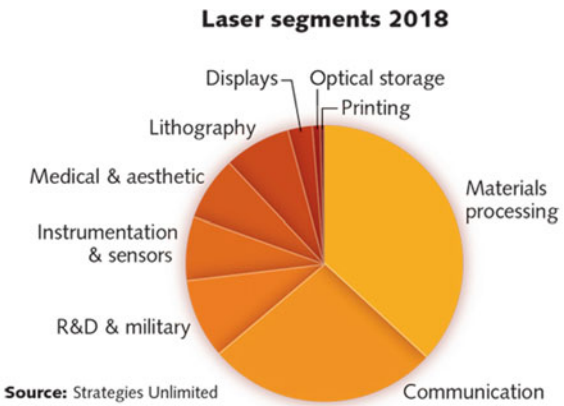


Fig. 2 Laser market segment (*Source* Laser Focus World [7])

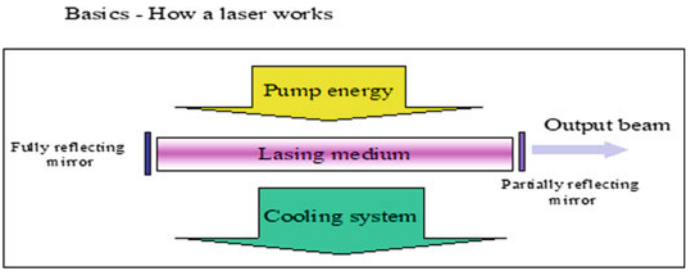


Fig. 3 Basic laser mechanism [1]

GM for laser heat treatment of steering columns. During the past decade, German auto manufacturers have installed hundreds of lasers for body-in-white welding purposes.

2 Why Lasers Are Attractive for Manufacturing?

The basic mechanism of a laser is shown in Fig. 3. Laser light is a stream of photons that interact with surface electrons of the materials it is processing. This mechanism is known as "inverse bremsstrahlung." Laser light, unlike conventional machine tools, does not have any mass or inertia. The beam can be focused to a very small spot concentrating the energy exceeding 10^5 W/cm^2. It is probably one of the few sources of energy with such concentrated energy capable of melting and ablating many of the engineering materials. Energy can be delivered through vacuum, air, or fiber. The beam can be shaped to conform to a particular surface. Shaping can be done both temporally and spatially. This characteristic provides enormous flexibility for manufacturing applications. Energy density can be varied with optics based on the power density needed for the specific manufacturing process. For example, heat treatment requires 10^3 W/cm^2 whereas welding requires 10^6 W/cm^2. Same laser can provide both intensity levels with simple optics. The optical beam can also provide photolytic processes breaking molecules by matching the wavelength of vibration of the molecular bonds. Coherence and spectral purity allow strange non-linear optical effects. Polarization, frequency doubling, diffraction, and multi-photon phenomena all found their way into the manufacturing floor. Moreover, optical energy source is highly amenable to automation.

3 Laser-Aided Manufacturing

Initially, lasers were dubbed as "Solution looking for Problem" but since 1070s, it has been used extensively for various applications from [A to Z] atom splitting to zapping of eyes. However, as shown in Fig. 2, material processing and manufacturing

Table 2 Laser power density versus different manufacturing processes. LCVD stands for Laser Chemical Vapor Deposition

Power intensity (W/cm^2)	Stage of heating	Associated processes
<10^5	Thermal conduction	Transformation hard, bending, LCVD
10^5	Melting	Welding, cladding
10^6	Vaporization	Cutting, drilling
10^7	Plasma production	Cleaning, shock hardening
10^9	Solid-state plasma	Shock hardening
>10^9	Atomic fusion	Femto second processes

captured the largest market share. Table 2 shows laser energy density needed for various manufacturing processes.

Laser energy density and interaction time have found its way to almost entire manufacturing field to fabricate components from nanometer to several meters. Figure 4 shows a rough map for the energy density, interaction time, and size of the object possible to be fabricated. Holy Grail for manufacturing is to control intensity, interaction time, and cooling rate to modify the microstructure to obtain certain properties for people to use (see Fig. 5). Most of the human endeavors for the laser-aided manufacturing for last five decades have been to develop process-parameter-structure-property relationships both experimentally and by mathematical modeling [3]. Different laser-based manufacturing processes are mentioned in the following sub-sections.

3.1 Laser Heat Treatment

It is used for transformation hardening and annealing of work-hardened materials needing energy density around 10^3 W/cm^2. Laser heat treatment has to follow same time-temperature criteria as conventional heat treatment. One additional criterion is that the substrate should have enough mass compared to heat-treated zone so that conduction rate between treated and untreated zone exceeds the critical rate for hardening. This self-quenching mechanism can also offer a very high cooling rate, sometimes leading to higher hardness than what is available through conventional quenching in water or oil [8].

General Motors has adapted laser heat treatment in 1978 for hardening of their steering column for improved life through wear resistance. Some of the cutting tool companies also apply that for localized hardening. Lasers can focus so precisely that even a tip of teeth of a hacksaw blade can be heat-treated (See Fig. 6). This provides

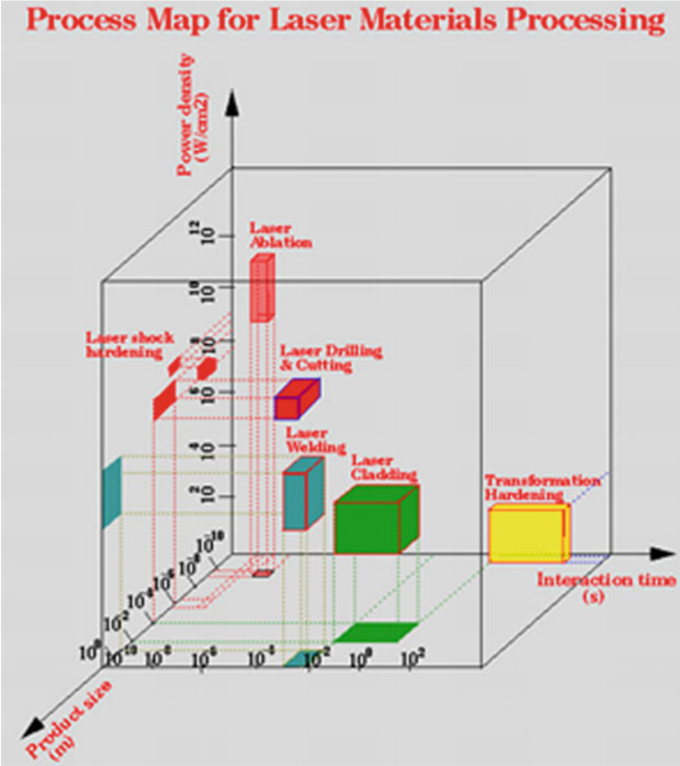
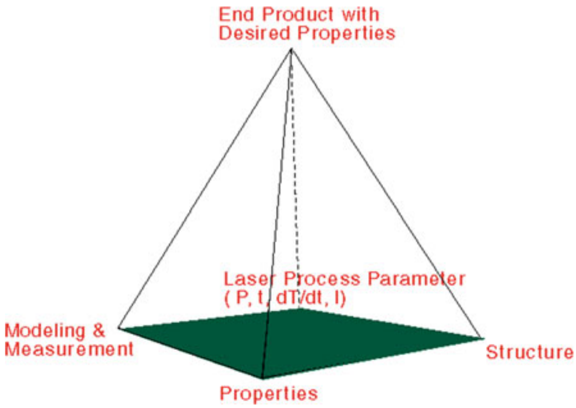


Fig. 4 Intensity and interaction time for different manufacturing processes

Fig. 5 Holy Grail for laser-aided manufacturing



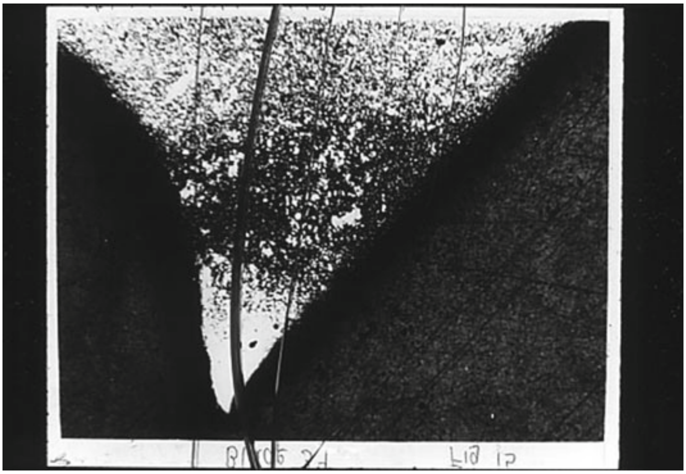


Fig. 6 Laser heat-treated tip of a 12 × 0.5 inch hacksaw blade

a combination of hardness and toughness for the blade. The same concept is also adapted by gear industry.

3.2 Pyrolytic Laser Chemical Vapor Deposition

Laser chemical vapor deposition is also another manufacturing application with similar low power density requirements like laser heat treatment. In this process, a substrate is heated in presence of gases which causes endothermic reaction to produce a reaction product. It is deposited on the substrate and another by-product is in the gas form that is pumped out [9]. This process can work with almost all the chemical combinations used by the conventional CVD process, but provides 10,000 times faster depositions [10]. LCVD can also follow photolytic route where laser wavelength is matched with molecular vibration to initiate the reaction [9]. In this case, the laser runs parallel to the substrate. The deposition rate in this route is much slower than that of pyrolytic route. LCVD is used sometimes in integrated circuit industry to repair faulty prints of the circuit.

3.3 Laser Surface Alloying and Cladding

It is another laser-aided manufacturing operation that made significant penetration in the market [3]. AT&T adapted laser surface alloying for their telephone connection jacks decades back to achieve longer life through wear resistance. Turbine blades industry employed laser cladding to repair the leading edges of the worn out blades

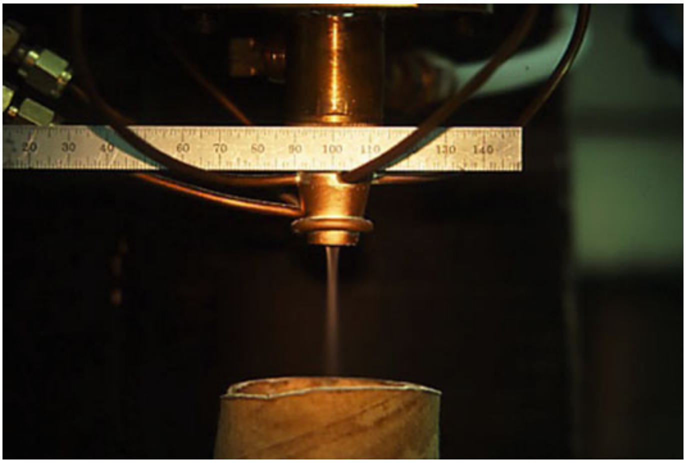


Fig. 7 Laser cladding with blown powder

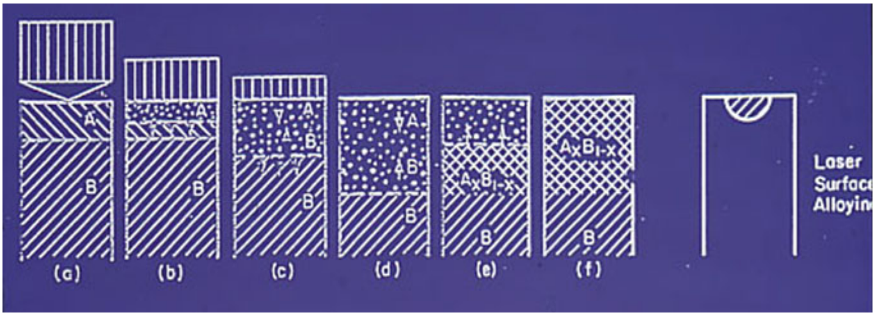


Fig. 8 Stages of laser alloying

since 1980s. These are non-equilibrium processes [11] capable of producing surfaces with tailored properties. In surface alloying, a coating of different material is applied on a surface in many different ways including electroplating, slurry, or powder blown through a nozzle (see Figs. 7 and 8). A high-power laser melts and completely mixes the coating creating a surface with composition that is a mixture of two different alloys. However, in cladding, coating composition is more or less kept with a bit of dilution from the substrate.

3.4 Additive Manufacturing/3D Printing

3D printing has captured the imagination of the manufacturing community worldwide since 2012 [12, 13]. April Issue of Economist magazine dubbed it as 3rd Industrial

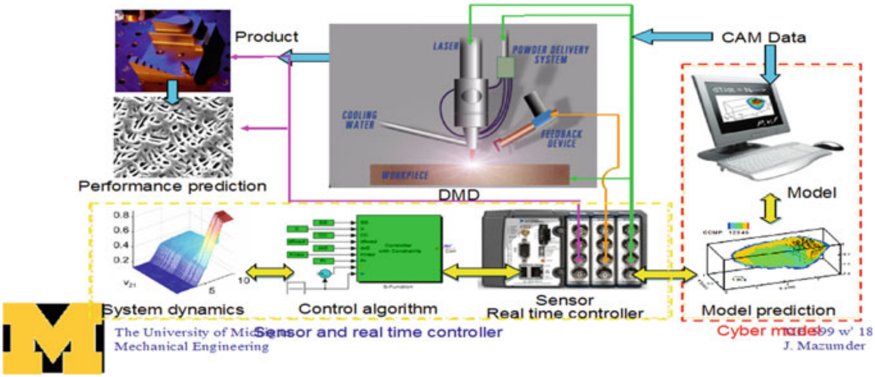


Fig. 9 Metallic additive manufacturing system

Revolution although route of it goes back thousands of years. In 2800 B.C., Egyptians made pyramids layer by layer, which is the basic principle of additive manufacturing. In modern reincarnation, Charles Hull [14] reported 3D printing from polymeric resins with the help of lasers in 1986. Subsequently, Joe Beaman [15] reported solid free form formation by melting plastic granules layer by layer with lasers. Mazumder [16, 17] reported rapid prototyping with metals with closed-loop control of laser cladding (see Fig. 9). Although 3D printing is being developed rapidly, non-laser processes such as extrusion-based resistance heating of polymer are getting adapted more rapidly due to lower cost.

3.5 *Laser Welding*

Laser welding has a wider footprint on the manufacturing floor [3, 18]. Automobile, aerospace, shipping, and chemical industry have adopted laser welding significantly. Keyhole formation without the need for vacuum is the attraction for relative thicker section (see Fig. 10). Keyhole formation means the depth is higher than the width of the weld as shown in Fig. 10. One of the high volume applications is in fabrication of tailored blank for car door as shown in Fig. 11. Laser being an inertia less tool, fixturing is much easier. Narrow heat-affected zone and precision welding are attractive for the users.

3.6 *Laser Cutting*

It is another widely used process. Due to its capability to cut profiles, laser cutting with high-quality edge has become very popular [3]. In laser cutting, highly focused beam with power density exceeding 10^6 W/cm^2 with assist gas is used as shown

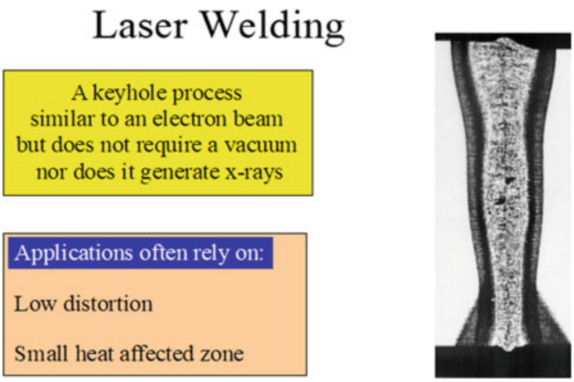


Fig. 10 Keyhole laser welding [1]

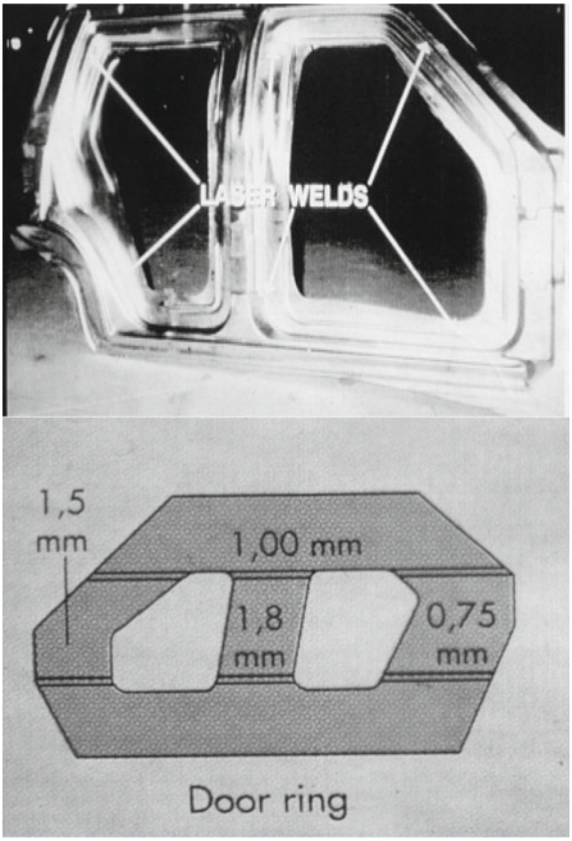


Fig. 11 Tailored blank [1]

in Fig. 12 (adapted from [1]). There are several modes of laser cutting as shown in Fig. 13 (adapted from [1]). Vaporization cutting needs highest power density. Oxygen is often used as an assist gas since it provides additional energy through exothermic reaction. Sometimes gear manufacturers use profile laser cutting to generate the teeth instead of machining. Even greeting card industry uses laser cutting of papers to produce intricate artistic greeting cards.

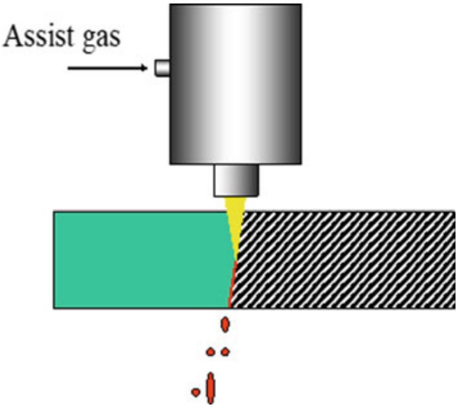


Fig. 12 Laser cutting

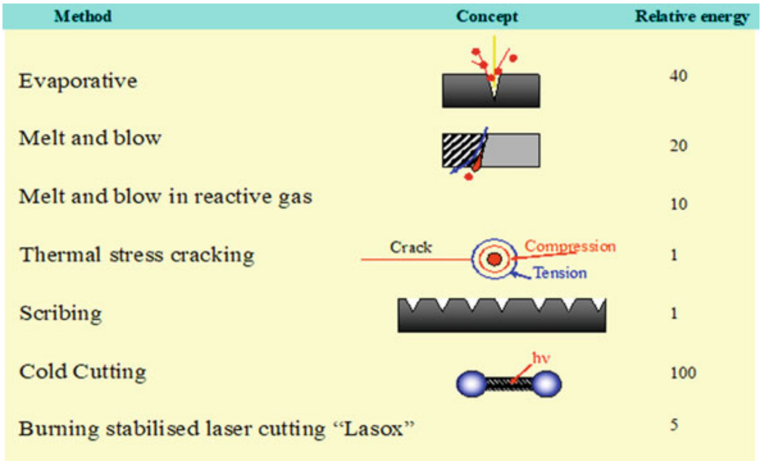


Fig. 13 Modes of laser cutting

3.7 Laser Drilling

Laser drilling [3] is used for making nipples for baby bottles. Also, it is used to make electrodes for Li-Ion batteries. Pulsed lasers are more popular for laser drilling. Lasers with 10^{-15} s pulse widths give the cleanest holes but commonly pulse width of 10^{-9} s is used for production. Laser drilling has two different modes. One is percussion drilling where a stationary laser beam evaporates the material to create the whole with a similar size to beam diameter. Another is called "Trepanning" where a laser beam is moved to cut a circular hole. Often oxygen is used as assist gas. For oxidation, sensitive materials like titanium, and inert gas such as argon is used. There are a few more applications such as laser shock hardening, laser cleaning, and laser marking.

3.8 Laser Shock Hardening or Laser Shock Peening

This technique is extensively used by aerospace industry [19] to provide compressive residual stress at the surface of aerospace components to increase the hardness and fatigue life. Compressive stress hinders fatigue crack growth. In laser shock hardening, the objects to be treated are often coated with black paint or tape to enhance absorption. Then, a thin layer of water is passed while the substrate is irradiated with a high-power laser pulse as shown in Fig. 14 [1]. Laser pulse width in the order of 10^{-9} s is most suitable for this process. A plasma is formed on the light-absorbing layer and the water confines the expansion of the plasma that creates a shock wave that propagates through the substrate consolidating point and line defects. This results in compressive residual stress.

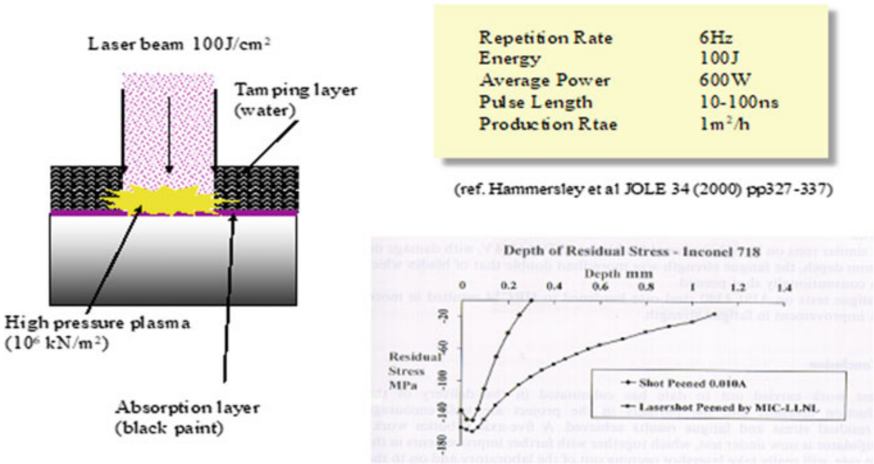


Fig. 14 Laser shock hardening

3.9 *Laser Cleaning*

It depends on the blast of laser radiation that can remove dirt from the surface. It is a quiet cleaning process without the need for solvent or abrasive. Fume generated by ablation can be easily removed by vacuum. The old church, damaged during WWII, in Dresden Germany was restored and every piece was reassembled after laser cleaning. Old structures with toxic lead paints can also be cleaned by lasers.

4 Summary

Lasers are used for a wide variety of manufacturing processes. The main reason for its popularity is its ease of availability with a wide range of intensity levels from fraction of W/cm^2 to 10^{15} W/cm^2 with precision. It is also amenable to automation, making it a useful tool for modern manufacturing. It is one of the most adaptable forms of energy sources for industry. Its popularity and applications have been continually increasing since its invention.

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