Chapter

Laser Surface Treatment

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Abstract

Laser surface treatment (LST) utilizes intense thermal energy of laser beam for modification, alloying, and cladding surface of substrate materials. In LST very high cooling rates of 104–106°C/s can be achieved. Such high cooling rate arrests the possibilities of segregation in the case of multicomponent systems. Moreover, very narrow heat-affected zone (HAZ) and easy automation make it suitable for large-scale industrial production. LST depends on many process parameters such as laser power, scan speed, focal length, spot size, substrate temperature, and type of material. Selection of proper range of process parameters for good surface quality is essential. Pores and cracks may arise due to improper selection of parameters. Multilayered, high-entropy, thermal barrier coatings using LST with good bonding with substrates have been developed.

Keywords: laser surface modification, laser surface alloying, laser cladding

1. Introduction

Metals and their alloys are one of the means to fulfill our imagination. With change in necessity, their utility is also changing. Today industries require materials that can meet the demands of challenging markets. In this age of miniaturization, we require materials that can form the framework for new technologies. Advanced biomaterials for bones and dentures with critical surface properties have been developed [1, 2]. These materials have shown to perform better than the available materials. Artificial bones of Mg and their alloys have been researched [3]. These may restrict the requirement of recursive surgeries in case of implants. In the nuclear industry, materials which can restrict the harmful radiations while themselves remaining neutral have been proposed [4]. Such materials may be able to improve the working conditions of nuclear industry workers and may restrict the radiation leakages in prolonged use. Chromium has been used for decades as a surface hardening and corrosion-resisting agent. In recent years there are some articles that discuss the effect of chromium on health [5, 6]. It has been found that few states of chromium may be the probable cause of cancer. Hence, alternate materials possessing properties similar to chromium coatings have been reported [7]. In an attempt to improve the efficiency of power plants, turbine blades which can handle high stresses have been tested [8]. These materials may help boost the limits of power plants, aircrafts, and other propulsion systems. The thrust of ever-expanding horizons of knowledge development of materials and surface properties has become essential.

Most of the advanced applications require superior surface properties such as high hardness, strength, wear resistance, corrosion resistance, high temperature oxidation resistance, and improved magnetic and chemical behavior. All these properties can be incorporated and developed by modifying the surface of the

Attributes	LSA	Electrodeposition	Thermal spray	CVD	PVD
Dilution	High	Nil	High	Nil	Nil
Bonding strength	High	Low	Moderate	Low	Low
Heat-affected zone	Low	Nil	High	Low	Low
Coating thickness	Moderate	Moderate	High	Low	Low
Repeatability	High	Low	Moderate	High	High
Controllability	High	Low	Moderate	High	High

Table 1.
Characteristics of different techniques.

components. There are wide varieties of surface modification techniques available. Some of these techniques are thermochemical coatings (nitriding, carburizing, cyaniding, etc.), electrodeposition, electroless deposition, spray coatings (flame spray, thermal spray coating, plasma spray coating, etc.), physical vapor deposition (PVD), chemical vapor deposition (CVD), laser surface modification (LSM), etc. These diverse techniques mutually form a branch termed as surface engineering. All these surface modification techniques have certain advantages and disadvantages. **Table 1** lists some of the desirable attributes and corresponding behavior observed with different processes. For precision coatings of thermally sensitive and multicomponent materials, usually laser material processing is employed. Due to its localized heating and rapid solidification rates, thermal distortion and segregation possibilities are diminished. Also, high energy density leads to melting of almost any metal [9]. High-energy-density laser beam produces high dilution and good bonding strength, and very low heat-affected zone can be developed. Other techniques usually suffer in one or the other reasons. Also, high repeatability and controllability makes it a suitable technique for industrial standards.

With the development in the automation sector, lasers having high accuracy and precision are available. Thus, in the last decade, a large number of literature dealing with application of lasers in various fields are available. These lasers may also be used to develop layer by layer lamina to develop a desired 3D structure. Laser-based techniques employed in 3D printing are selective laser melting and sintering. A part program of the 2D structure to be manufactured is developed. These 2D structures of the same or varying sections are developed above one another. These adjacent layers join together and form a required 3D structure. Hence, laser printing is very similar to surface treatment processes. This chapter in particular presents the ongoing trends of laser surface treatments in melt regime, i.e., it discusses techniques such as laser surface alloying, laser cladding (LC), selective laser melting, and laser glazing. Although the basis of these techniques is same, these techniques differ from one another in the desirability of final surface properties achieved. Numerical simulation and application of these techniques have been discussed.

2. Selection of laser

Many aspects are considered during selection of laser for LST processes. Some of the desirable characteristics are presented in the flow chart shown in **Figure 1**. The material to be processed is one of the factors for selection of laser type. Heat-sensitive materials and refractory materials are generally processed in pulsed mode [10–15]. It is also observed that the solidified structure of developed materials may be different in the case of continuous and pulse laser modes [16]. **Figure 2** shows the relationship between reflectivity of a material and wavelength of radiation [17]. Materials such as aluminum which have very low absorptivity are usually processed with low wavelength pulses [18]. Besides, these desirable properties also significantly affect the selection of laser for a particular application [19].

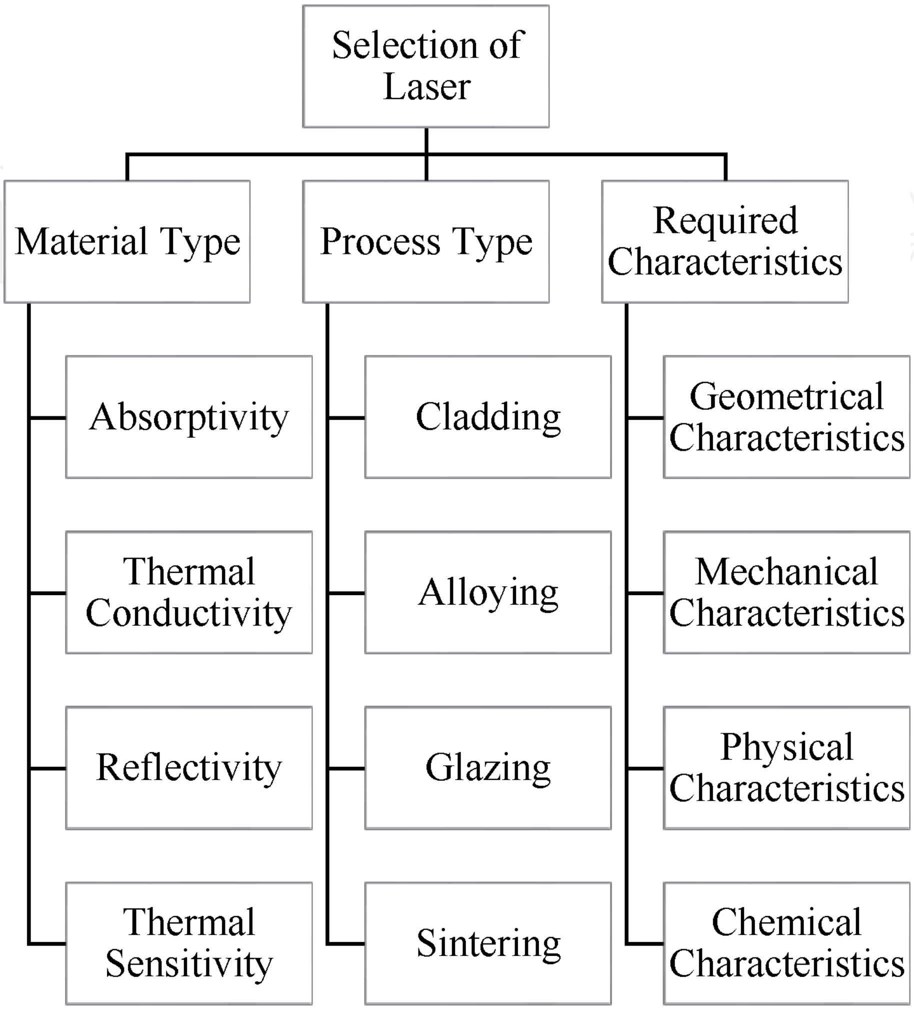

Figure 1.
Constraints considered in selection of laser source type.

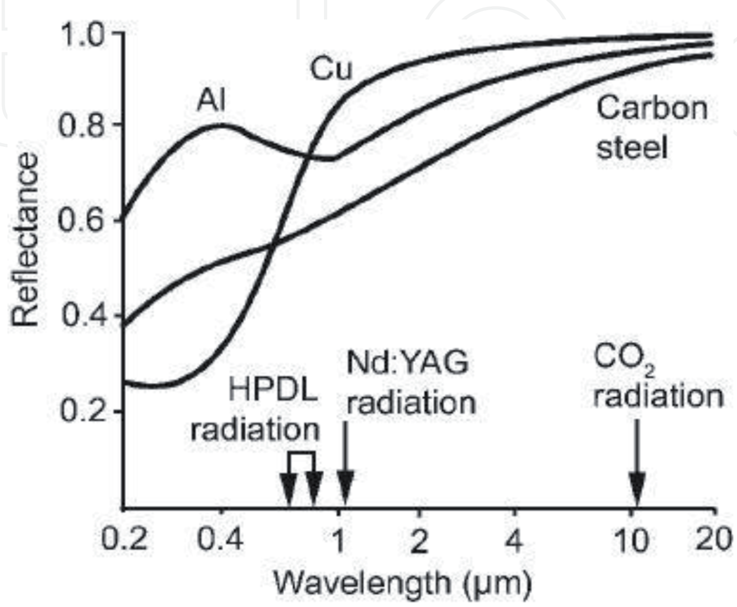

Figure 2.
Reflectance of substrate vs wavelength of radiation for some materials [20].

The type of process also affects the selection of laser. Generally surface alloying requires a large amount of heat to melt considerable amount of substrate surface. Thus high-energy lasers are required. Glazing and sintering usually employ low-energy lasers, whereas cladding uses intermediate-energy lasers.

3. Laser surface treatment processes

Extensive laser surface treatment techniques are available. Laser surface treatment usually modifies the topography, phase composition, and microstructure of a substrate material to improve its surface properties. When a laser is incident on a substrate material, laser radiations are absorbed by conduction electrons near the surface region (in nm range). These excited electrons collide with lattice ions and rapidly produce heat. The heat produced in this thin layer is conducted to the bulk substrate. This causes swift heating of a layer of material, having a thickness greater than the characteristic radiation absorption depth. As soon as the laser irradiation is stopped, the substrate material cools due to heat transfer. **Figure 3** presents a block diagram of laser interaction with substrate.

These thermal cycles may possibly cause phase transformations, topography, and microstructural variations. The extent of these changes depends on the behavior and type of material irradiated, the maximum temperature attained, and heating and cooling rates experienced. All the above said factors depend on the laser power density and interaction time between laser and substrate material. Laser surface treatment techniques are differentiated on the basis of temperature observed at the surface due to irradiation. If surface temperature attained due to laser irradiance is less than the melting temperature of a material, solid state transformations can be observed. Such a system is observed in hardening, shock peening, and engraving. When the surface temperature obtained is greater than the melting temperature but lower than the vaporization temperature of the substrate material, melting of substrate surface takes place. This is the most widely used regime for surface modification. Techniques such as laser cladding, laser alloying, laser glazing, and selective laser melting fall under this regime. If the surface temperature is greater than the vaporization temperature of the substrate, vaporization of substrate surface takes place. This regime is used in laser machining techniques such as laser drilling, cutting, and contouring. **Figure 4** presents a block diagram of this classification.

3.1 Laser cladding

Laser cladding technique is employed to produce coatings with enhanced surface properties or to repair surface defects of different components. LC employs high energy density of laser beams to melt and alloy the surface of substrate materials. Due to high energy density, most of the metals can be melted and alloyed. Usually when the dilution percent is less than 10%, LC is meaningful because low concentration of substrate is desired in LC. Thick to moderate layers of almost any material can be developed. **Figure 8(a)** shows a cross-sectional image of clad bead.

The material to be deposited on a substrate may be supplied using two techniques: preplaced powder deposition [21–25] or codeposition method [26–30].

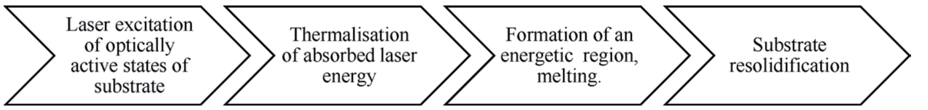

Figure 3.
Laser material interactions.

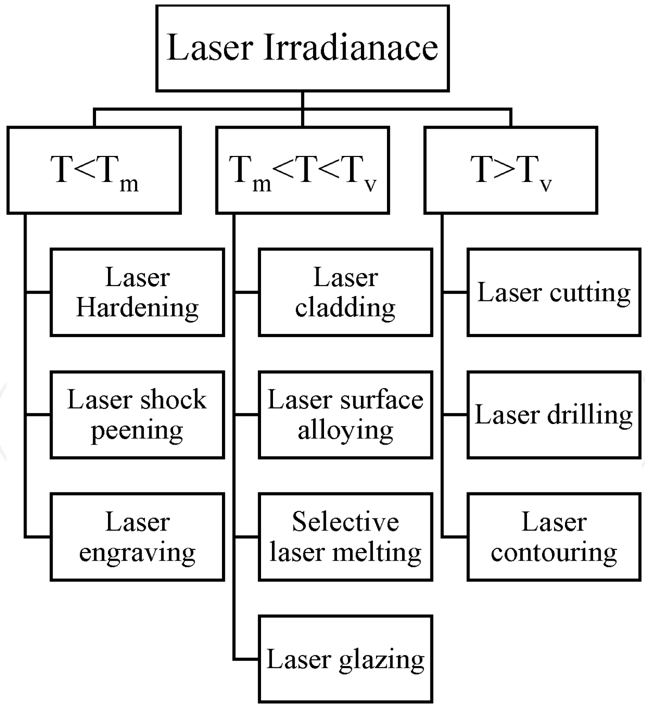

Figure 4.
Classification of laser material processing techniques.

These methods differ in the supply of clad material. In the first method as shown in **Figure 5(a)**, the powder to be clad is first mixed with certain adhesives (polyvinyl alcohol) to form slurry. This slurry is placed above the substrate as a uniform coat and allowed to dry and harden. This is done so that it can withstand the pressure of the shielding gas and particle nature of laser.

In the second method as shown in **Figure 5(b)**, the powder to be clad is fed through the powder feeder nozzle onto the laser beam and subsequently on the molten pool. This powder feeding can be done at various angles through the laser beam. When the angle of feeding is zero degrees, it forms a coaxial feeding system. Some authors have also studied LMP using different types of nozzles [31, 32]. Generally, off axis, four stream and coaxial nozzles have been employed. **Figure 6** shows the gas and particle flow patterns for various nozzles. Thus, cladding of substrate is possible using both the techniques.

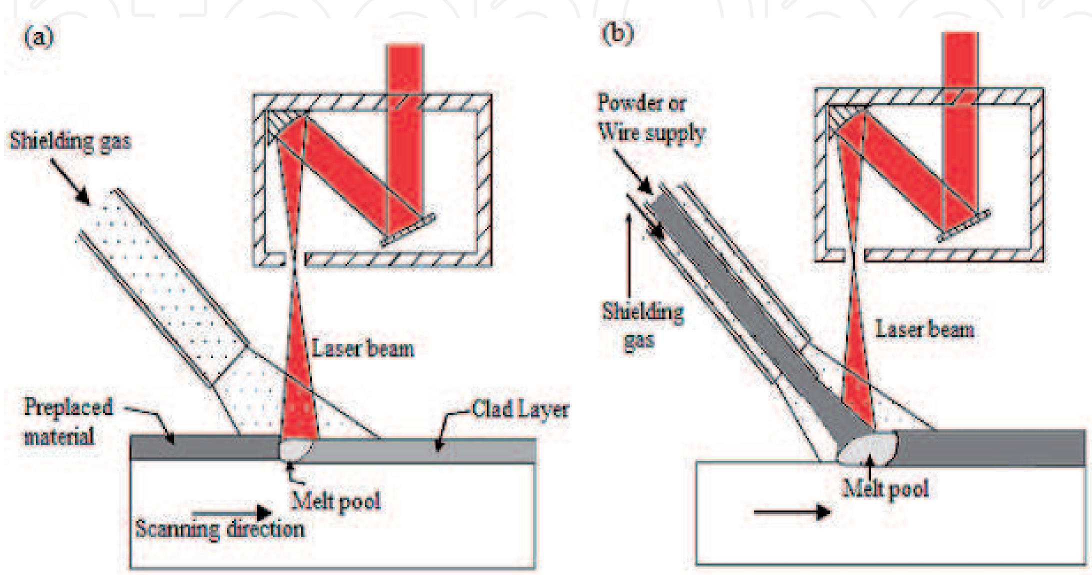

Figure 5.
(a) Preplaced technique and (b) codeposition technique [33].

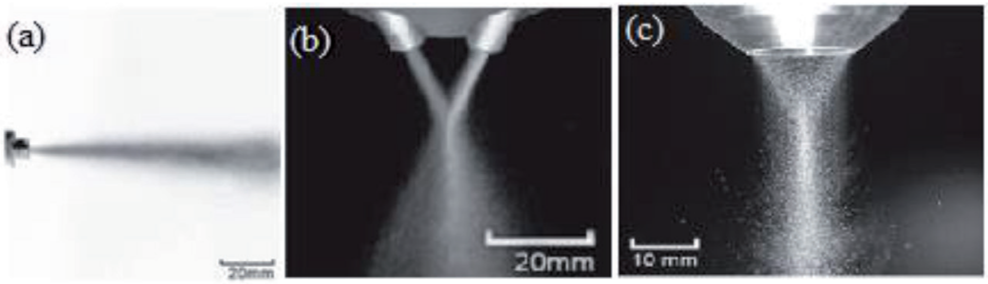

Figure 6.
Gas and particle flow for (a) off focus, (b) four stream, and (c) coaxial nozzles [32].

Through extensive review of articles, it was observed that beads produced using powder preplaced method are prone to more defects. This may be attributed to the presence of a bonding agent which vaporizes during laser beam interaction. Also, the height of clad can be manipulated in a codeposition method which is difficult in preplaced technique [34].

The type of microstructure formed depends on the temperature gradient (G) and solidification rate of crystal (R) [35–37]. High G/R ratio leads to planar structure, with decrease in G and increase in R columnar structure being achieved, and low G/R ratio leads to equiaxed dendritic structure. In LST high cooling rates (10^3–10^8 K/s) can be achieved [38]. Hence in LST generally dendritic structure is visible. Change in structure can also be realized with change in mode of laser. It is observed that in continuous laser mode, columnar dendritic structure was formed which was oriented towards the center of clad bead, whereas in pulsed laser mode, stacks of dendrite were randomly oriented. This was due to cyclic melting and resolidification phases, leading to progressive change in the molten pool. **Figure 7** shows the LC using continuous (a) and pulsed (b) mode.

3.2 Laser surface alloying

Laser surface alloying (LSA) is a similar process to LC but using high energy density. LSA sample is shown in **Figure 8(b)** [40]. It is observed that dilution percent is greater than 10%. Hence, no clear distinction up to a certain depth can be observed, and alloy bead has some proportions of substrate material. Usually, LC is employed in applications requiring entirely different properties at the surface and core, whereas LSA is employed in applications requiring change in properties for greater depth.

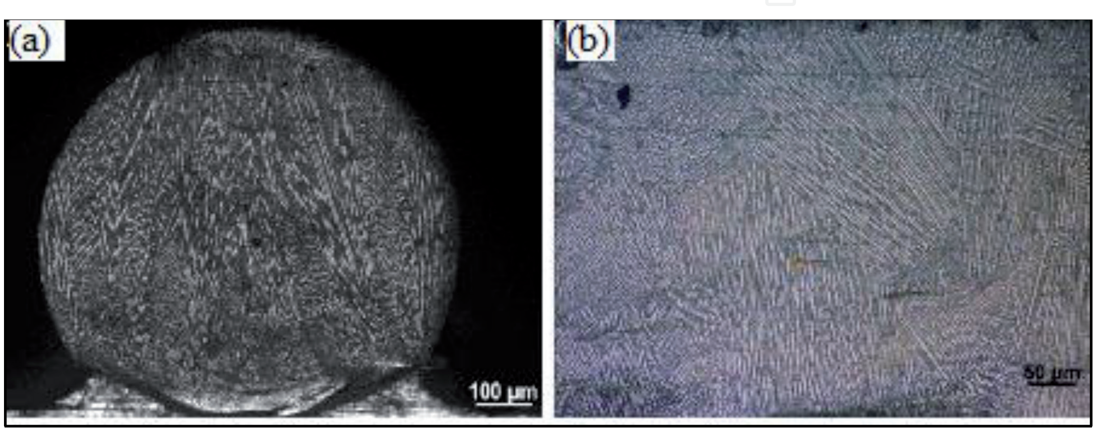

Figure 7.
LC using (a) continuous mode and (b) pulsed mode [39].

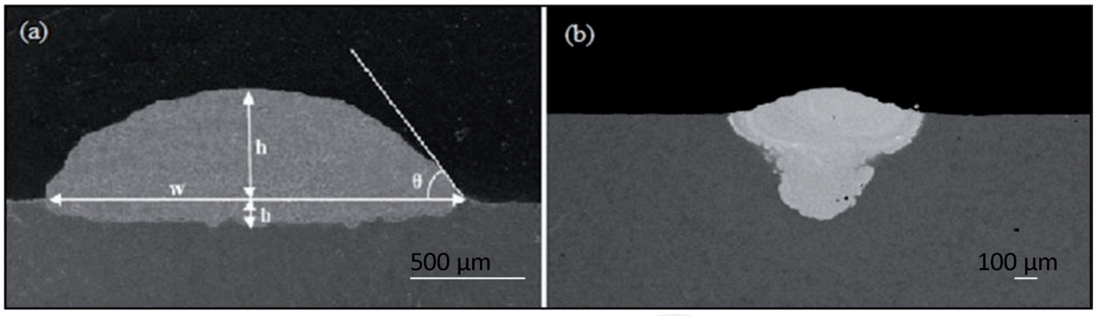

Figure 8.
Cross-sectional images of (a) laser clad [30] and (b) laser surface alloyed bead [40].

3.3 Selective laser melting

Selective laser melting (SLM) utilizes laser energy to create 3D parts using a 3D CAD sketch of the part geometry to be produced. The 3D model is then broken to a 2D stack of layers which form the required geometry. These 2D layers are created by laser scanning over the cross-sectional area. This scanning of laser melts and bonds particles together to form a thin layer. Repeating this process, a subsequent layer may be produced and altogether bonded to previously produced layers. These formed stacks of 2D layers represent the final 3D required geometry. Selective laser sintering (SLS) is a similar process to SLM, but in SLS complete melting of powder does not take place. SLS uses low-power lasers for fabrication of 3D parts compared to SLM. Thus, the final products formed using SLS usually have high porosity and require impregnation of different materials. **Figure 9** presents the steps in SLM.

Literatures suggests that SLM is successfully applied to aluminum and its alloys, high-speed steels, nickel, and copper alloys. The main problems with SLM are porosity, cracking, oxide inclusion, and loss of alloying elements. Porosity may be reduced by proper selection of laser energy density for specific material. Cracking can be reduced by decreasing the cooling and solidification rate.

3.4 Laser glazing

Laser glazing (LG) is a surface melting method using a continuous high-energy laser beam which traverses the surface of a substrate, generating a thin layer of melted material. After the solidification of this thin melted layer, the material's surface appears glassy; therefore this method is termed as laser glazing. Researchers have done LG to improve surface properties [42–44]. It employs low peak power;

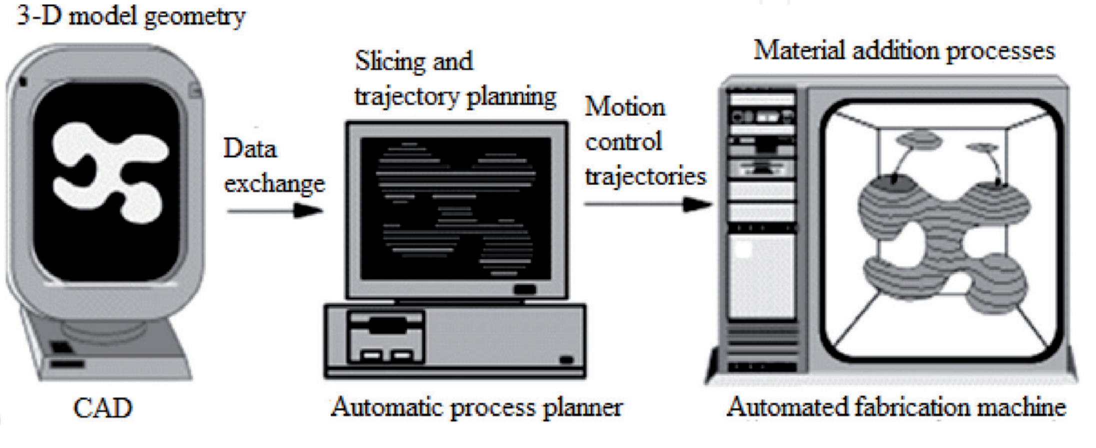

Figure 9.
Steps in SLM technique [41].

hence vaporization of surface materials is restricted. LG is used to level the surface and develop a dense re-melted layer. Due to such a system microhardness, erosion resistance and thermal shock behavior of the substrate may be improved.

4. Numerical modeling of laser surface treatment processes

Since LST processes are highly nonlinear processes, hence for clear understanding of the process, numerical modeling is essential [45]. Besides laser beam interaction with the substrate, LC and LSA impose additional constraints of clad and alloying materials that may be supplied in the form of preplaced powder or through powder feeder. In case powder is supplied through powder feeder, then the study of powder flow dynamics becomes important. Hence, LC and LSA processes can be broken in three stages: powder stream dynamics, melt pool region, and quality variables. Experimental study of laser surface treatments is not sufficient to understand complex phenomena such as powder stream pattern, laser and substrate interaction, heat transfer mode, and melt pool behavior. Hence, analytical models and numerical simulations have been developed. Some of the brief advancements and understandings in these areas are presented.

4.1 Powder stream dynamics

Powder stream dynamics is a significant area in the blown powder technique because we can predict powder stream characteristics such as motion, flow profile, powder with laser system interaction, etc. These parameters may be further used in optimization of parameters and calculate powder efficiency. The behavior of powder flow is governed by the type of nozzle employed. The turbulent flow of carrier gas can be assumed to be a continuum; hence Navier-Stokes equations can be used. A dispersed powder in carrier gas is generally solved using the Lagrangian equation [46]. During powder–laser interaction, attenuation of laser energy takes place due to absorption, reflection, radiation, beam scattering, and ricocheting of powder particles. Models based on particle attenuation [47], ray tracing [48], resolution [49], and light propulsion force model [50] have been reported to predict the behavior of attenuated laser energy fairly. Finally, powder substrate interaction depends on the standoff distance. For high convergence the substrate should lie at the focus of the nozzle [51].

4.2 Melt pool

The substrate melts due to absorption of remaining incident laser energy. The focuses of interest in this region are heat transfer, geometry of melt pool, fluid flow velocity, cooling rate, and solidification rate. These variables have been calculated using kinetic approach [52], volume method [53], and finite element method [54, 55]. Usually commercial multi-physics platforms such as ANSYS, COMSOL, FLUENT, and ABAQUS are employed for the problem.

4.3 Quality variables

The simulation of desirable properties is usually done in combination with developed thermal model. Phase transformation models along with thermal models provide base for the measurement of quality variables. Diffusion and diffusion-less phase transformations may occur in different material systems. Diffusion phase transformations have been modeled using the Johnson-Mehl-Avrami equation, while diffusion-less phase transformations are modeled using the Koinstinen Marburguer equation [56, 57]. Hardness measurement of a treated surface has been predicted by coupling thermo-kinetic relation and thermal model [58, 59]. Residual stresses develop in laser-treated parts; these lead to crack and distortion. The finite element method has been used to solve coupled elastic, plastic, and thermal strain equations with phase transformation equations [60, 61].

5. LST applications

LST has a wide application in aerospace, automobile, medical, nuclear, oil recovery, and refinery industries [62–66]. Aluminum and its alloys are widely used in aerospace industry; they have been efficiently clad with other novel metals to improve their surface properties [67]. Stainless steel is used in automobile and household applications [68, 69]. Titanium and its alloys are used in the medical sector [70]. LC on Ti6Al4V has been studied frequently to improve its surface properties [71].

Materials	Application	Improvement	Author, year
CMSX-4 (Ni-based super alloy)	Repair of turbine blades	This method helped to develop monocrystalline CMSX-4	Rottwinkel, 2016 [73]
Stellite-6/WC on B27 boron steel	Repair of tools for soil cultivation	Formation of intermetallic compounds improved the wear resistance	Bartkowski, 2016 [74]
NI40 and NI60 on C60 steel	Improvement of barrel-screw system in plastic injection molding	Ni-Cr alloy clad improved the microhardness	Zarini, 2014 [75]
CPM9V steel on H13 tool steel	Repair of molds and dies used in hot and cold working	Presence of compressive stress due to formation of martensite phase	Paul, 2017 [76]
Grade C wheel U75V rail with 316L, 420, 410	Repair of damaged railway wheels	The wear rates decrease with increased hardness of the clad materials	Zhu, 2019 [77]
Titanium hydroxylapatite on Nitinol	Coating on Nitinol implants to restrict nickel release	Modulus of elasticity of coated samples falls in the range of 6–30 GPa which is similar to the natural bone	Chakraborty, 2019 [78]
Mg-Zn-Dy alloy casted and laser melted	Restrict in vitro degradation and improve tissue integration	Improvement in in vitro degradation due to formation of insoluble protective layer	Rakesh, 2019 [79]
Powdered Co29Cr9W3Cu alloy	SLM is used to develop Co29Cr9W3Cu alloy joint prostheses	Initiation of crack is arrested due to plastic deformation caused by strain-induced martensitic transformation	Lu, 2019 [80]
Ti powder on Ti6Al4V substrate	Improve in vitro biocompatibility capacity of the titanium deposits to be used as medical implants	In vitro test of samples in Hank's solution shows that the leaching was within the desired values	Nyoni, 2016 [81]

Table 2.
Some applications of LST.

LST applications can be classified in two categories. First is remanufacturing or refurbishing products to restore their properties and dimensions [72]. Second is development of new materials with improved properties. **Table 2** presents some critical applications of LST.

6. Conclusion

Laser surface treatment may be employed to provide advanced surface properties to a substrate material. The melt pool regime in laser irradiance is utilized to completely modify the surface properties. The interaction of laser with alloy/clad powder, laser and substrate material, powder particles, and substrate materials is important for clear understanding of the problem. Numerical-based techniques have provided a way to optimize, standardize the processes, and reduce wastage during actual processing. These techniques have a vast application horizon, i.e., from medical implants to turbine blades, all can be modified using these techniques.

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