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REVIEW ARTICLE

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Review on mechanism and process of surface polishing using lasers

Abstract Laser polishing is a technology of smoothening the surface of various materials with highly intense laser beams. When these beams impact on the material surface to be polished, the surface starts to be melted due to the high temperature. The melted material is then relocated from the 'peaks to valleys' under the multidirectional action of surface tension. By varying the process parameters such as beam intensity, energy density, spot diameter, and feed rate, different rates of surface roughness can be achieved. High precision polishing of surfaces can be done using laser process. Currently, laser polishing has extended its applications from photonics to molds as well as bio-medical sectors. Conventional polishing techniques have many drawbacks such as less capability of polishing freeform surfaces, environmental pollution, long processing time, and health hazards for the operators. Laser polishing on the other hand eliminates all the mentioned drawbacks and comes as a promising technology that can be relied for smoothening of initial topography of the surfaces irrespective of the complexity of the surface. Majority of the researchers performed laser polishing on materials such as steel, titanium, and its alloys because of its low cost and reliability. This article gives a detailed overview of the laser polishing mechanism by explaining various process parameters briefly to get a better understanding about the entire polishing process. The advantages and applications are also explained clearly to have a good knowledge about the importance of laser polishing in the future.

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1 Introduction

Lasers are devices which emit high power beams with the process of optical amplification by stimulated emission of radiation. The term LASER itself depicts light amplification by stimulated emission of radiation. The advent of new materials like ceramics, aluminates, super-alloys, metal-matrix composites, and high-performance polymers along with the sturdy need to process complex shaped parts results in an increasing demand for advanced material removal process [1]. Laser beams always travels in straight lines as a versatile and serves as a high energy source. Surface smoothening of complex and freeform surfaces has been one of the major challenges faced by the modern industrial world. Laser polishing proves as a solution to these challenges.

It is essential to mention the conventional methods of polishing, such as manual, mechanical, and electro chemical polishing, which require a long time and high cost for the polishing process. In addition to that, it requires highly qualified workers to avoid further damage to the surface. Almost all the conventional methods of polishing do not allow a single step process in processing the material. Limited use of automation makes these types of polishing methods less attractive to manufacturers. Willenborg [2], Perry et al. [3], and Wang et al. [4] are some of the researchers who has given laser polishing a firm base and some valid theories for how to effectively use the process parameters to get highly smoothened surfaces after polishing. This laid the milestone to a new era in the process of polishing or surface smoothening of complex shaped metals. Unique features of lasers made it favorite for manufacturers. The three main indicators which help in the assessment of a surface finish process are (1) topographic quality, (2) functionality, and (3) aesthetic properties. There are mainly three categories in the process of surface finish process, i.e., mechanical, electro chemical, and thermal energy. Among these, laser polishing comes under the thermal energy process which uses highly intense beams for the surface smoothening. Studies have proved that output power in the range of 50–100 W is suitable for laser polishing with high repetition rates and scan speeds.

The principle of laser polishing is surface smoothening by the process of re-melting and subsequent solidification of the surface as shown in Fig. 1 [3]. Laser polishing emerged as one of the new technologies of highly surpassing method of attaining highly super finished and smoothened surfaces. Laser polishing is a complex thermodynamic process in which highly intense laser beams impact on metal surfaces which then melts a thin layer present on top of metals. It can be done at two levels, i.e., macro and micro levels. Laser polishing can be done for almost all metals and it has been used to polishing ceramics and glass as well, thus proves to be one of the most promising polishing technologies available currently. This point makes clear that limitation of using lasers for the process of polishing of materials is invalid. Laser polishing can be incorporated in almost all kinds of materials. When the laser beam interacts with metal surface a melt pool is created on a thin layer of the metal. This melt pool which is in the liquid state is then redistributed around the adjacent area of metals under the multidirectional action of surface tension. No material removal takes place while re-melted as the metals gets re-solidified in the same surface. It is based on the optimal control of the process parameters the laser polishing process can be made more effective. Surfaces with high smoothness rate is most favorable in medical and industrial sectors as well. Different researchers have developed various experimental and numerical models for achieving this result. Perry et al. [5] performed laser polishing on micro surfaces in titanium alloys using pulsed laser beams where spatial frequency was analyzed using initial surface topography of the metal surface which gave better results for final smoothness. Ukar et al. [6] developed an analytical model which helped to verify the existence of two regimes, i.e., SSM and SOM.

This paper intends to give a detailed overview about laser polishing as there is not much work done on this topic in particular. Ultrafast lasers with high power and energy density can be used to create a more enhanced surface and help in formation of micro and nano structures [7]. Despite numerous advantages, there are many disadvantages which are obvious to occur during a manufacturing process. The primary objective of this first attempt is to review the laser polishing technology in the context of metallic surfaces and to present a critical snapshot on its performances as reported in previous publications.

2 Laser polishing mechanism

Laser polishing is a finishing process which mainly includes the melting of a thin layer of metal surface without any cracks or surface defects. This process aims at smoothening those peaks that are found on metals to an intermediate range below the peaks. Figure 2 clearly shows the polishing mechanism using lasers. The dotted lines represent the area where the peaks which is the rough surface should come down to and when this target is reached the surface can be said as a polished surface.

Laser polishing are mainly done at three levels:

a) Polishing by large area ablation in which large surfaces undergo polishing;

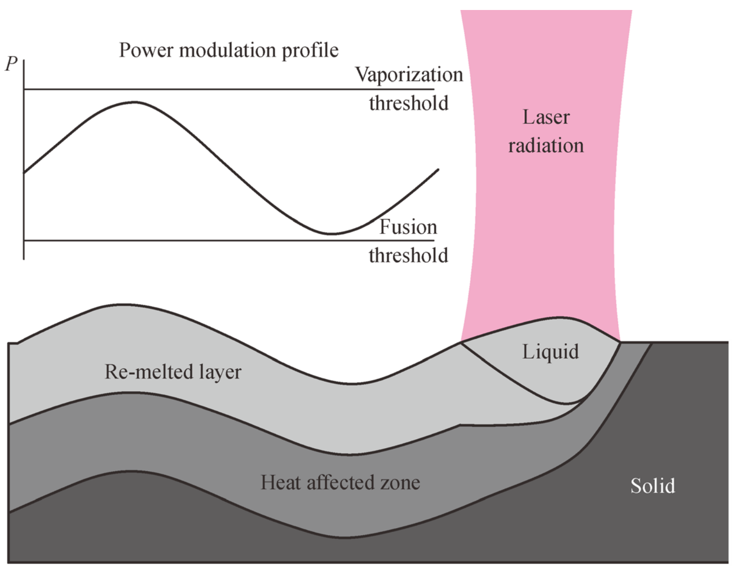

Fig. 1 Laser polishing working principle [3]

b) Polishing by localized ablation in which by controlling power density only rough surfaces are melted to reach a surface level;

c) Polishing by re-melting.

Figure 2 shows the re-melting process more clearly. The peaks that represents the roughness of surface are melted to the lower valley levels. Furthermore, two types of areas are mainly polished using lasers which are the macro and the micro surface as discussed below.

2.1 Macro polishing

Macro polishing is mainly done with a continuous wave laser radiation. The polishing allows a range of 10–80 μm to be polished with continuous re-melting of the top surface layer of the sample. The re-melting depth must be chosen according to the material and the initial surface roughness. Normally, fiber-coupled lasers are used with laser powers of 100–300 W. The processing time is between 10 and 200 s/cm^2 depending on the initial material surface roughness, the type of material and the roughness rate to be achieved [2,8]. A polishing rate of 1 min/cm^2 is achieved with laser macro polishing. The roughness depends on the thermophysical properties of material such as heat conductivity, surface tension, viscosity, melting and evaporating temperature, the initial surface roughness of the material to be polished, homogeneity of the material.

As per the results obtained from the experiments done by Willenborg [2], the following roughness rate is achieved by metals such as steel, bronze, titanium after laser polishing using macro and micro subvariant.

Table 1 [2] shows the effect of micro and macro polishing on different metals. It is clear from the above table that micro polished surface produces more gloss to surface and takes less processing time for the polishing process.

2.2 Micro polishing

During the laser polishing, the laser beam is moved over the surface to be polished where micro polishing takes place with pulsed laser radiation. Using this type of polishing only a pre-processed surface can be polished (i.e., ground and milled). The most important parameters for micro polishing are pulse duration and radiation intensity. A polishing rate of 3.3 s/cm^2 can be obtained with micro polishing [9]. The difference between laser micro polishing with other laser polishing process is the laser spot size and a constant energy density [8]. Micro polishing is a discrete process with a re-melting depth in the range of 0.5–5 μm [10]. Figure 3 shows that re-melting on metal surface is done using micro polishing. The molten material is already re-solidified when the next laser pulse hits the surface and creates a new molten pool. The intensity of laser beam must be chosen according to the pulse duration and the type of material which is going to be processed. Usually in this process a fiber coupled Nd:Yag Lasers or Excimer Lasers are used. Micro polishing always provides a micro smoothened surface, thus giving a high

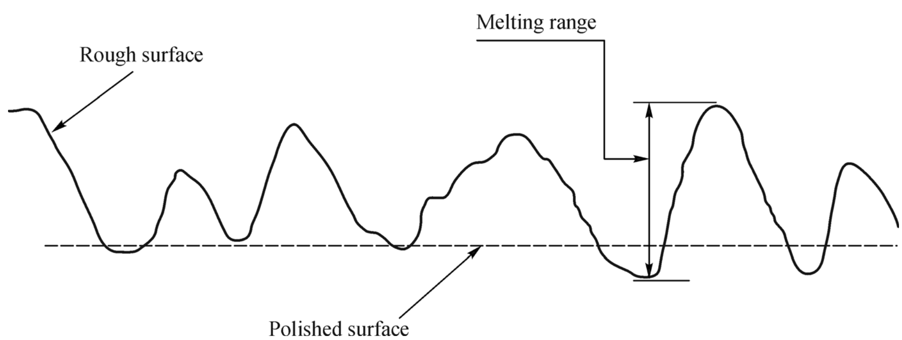

Fig. 2 Principle of laser polishing by melting

Table 1 Polishing results with subvariants macro and micro [2]

Metals	Subvariant	Initial roughness, Ra/μm	Roughness after laser polishing, Ra/μm	Processing time/(s·cm^{-2})
Tool steels	Macro	1.0–4.0	0.07–0.15	60–180
	Micro	0.5–1.0	0.30	3
Titanium, Ti-6Al-4V	Macro	3.0	0.50	10
	Micro	0.3–0.5	0.10	3
Bronze	Macro	10.0	1.00	10
Stainless steel	Macro	1.0–3.0	0.20–1.00	60–120

gloss surface [2,11]. Perry et al. [3,5,12] have studied and done experiments on micro milled Ni and Ti-6Al-4V using a 250 W, 1064 nm Q-Switched laser where an optical surface roughness of Ra = 115 nm is reduced to 77 nm with a laser pulse duration of 650 ns and a frequency of 4 kHz with a scan velocity of 35 mm/s.

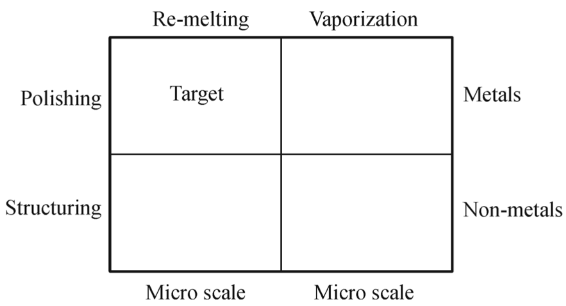

Fig. 3 Micro scale polishing

3 Mechanism of surface roughness reduction

There are two main mechanisms for reducing the roughness of a surface, namely, shallow surface melting (SSM) and surface over melt (SOM). According to previous studies, SSM region is a result of the capillary pressure and liquid curvature caused by the shallow melting of micro asperities that would fill the 'valleys' of the metal surface eventually with the molten metal [13]. This region can also be termed as 'a partially melted metal surface' [14]. In the SSM region due to the partial melting of the surface, the melted layer thickness is less than the peak-valley distance but if the energy density is higher the result would be *vice versa* [15]. The melted metal flows from peaks to valleys under the capillary pressure, where the valleys would be filled with molten metal from peaks which ultimately result in reduction of surface thickness [15,16].

When there is an increase in the energy density, the thickness of the melt pool would be higher than that of the peak-valley distance which in turn makes the entire metal surface into a melt pool. This causes a lower peak-to-valley frequency with higher amplitudes, which ensue to an increase in the surface roughness of the metal surface after the solidification process. In 2003, a thermophysical model was developed for analyzing the effect of deep melting in polished surfaces in the SOM regime [17]. With the help of an optical and scanning electron microscopy it is possible to identify the various textures in the surface [18,19]. The surface roughness depends on the scanning speed as well where in the SMM regime, the roughness value Ra goes down than the initial value of the surface with reduction in scanning speed. If this scan speed is further decreased, SOM region would be the result with an increase of Ra value [17,19].

Figure 4 [17] depicts a schematic diagram which shows the effect of SOM mechanism on metal surface and its periodic changes. When a focused laser beam hits the surface of the metal, it progresses in a rectangular track at high speed which causes the molten material to be pulled away from the solidifying front. Ripple formation takes place on the metal surface as shown in Fig. 4 [17]. When the material gets solidified it results in a wavy surface as this material displacement is caused due to the thermal gradient between the laser beam and the solidifying front.

Notably the final surface after the process of solidification depends on the factor that which regime has the priority (higher value). This happens as the peak-valley distance is not constant. In addition to that the type of regime formed would be based on the process parameters. According to some authors [20,21], in order to have a top-notch surface, the curb of process parameters should be held tight.

In laser polishing usually preferred method is to partially melt the metal surface rather than to make it completely into a liquid form [14]. The wavelength of a laser typically affects the polishing process. If the wavelength of laser is more the laser power will be high and thus with a high-powered laser the polishing process is much faster. However, a better polished surface can be obtained while using low power lasers. As discussed earlier, continuous wave lasers use more power than pulsed lasers [2,22]. The thermal field used by Ukar et al. [15] in his experiment to determine the thickness of the melted layer can be regarded as a marking point where the transition from shallow melting and SOM regimes takes place.

4 Typical laser polishing processes

4.1 Pulsed laser polishing

Pulsed laser polishing is mainly done in micro polishing of surfaces. Pulsed laser beams are discrete beams which hit the metal surface once and create a molten pool and then the re-solidification takes place before the next beam hits the metal surface as shown in Fig. 5 [23]. Mainly pulsed lasers are chosen based on the pulse duration and the intensity of the laser beam.

This process illuminates the sample surface with long (hundreds of nanoseconds) laser pulse at a fluence that causes surface melting from 10 to 100 nm inside and out, with insignificant removal. Because of liquefying of the surface, the surface tension work to smooth surface severities. The rate of surface flow is controlled by consistency and results in damped surface motions. The low power requirement of pulsed lasers adds as another advantage when compared with a continuous wave laser. On the damping out of the motions within the time that the surface is molten, a smoother surface would come about upon re-solidification. What makes this process one of a kind is its capacity to specifically clean smaller scale

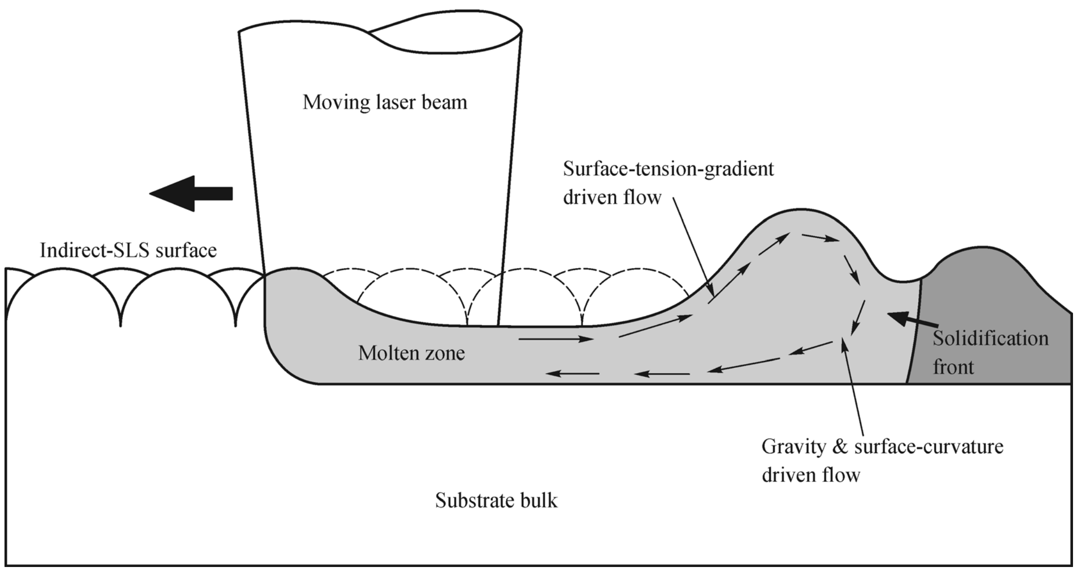

Fig. 4 Surface periodic formation during SOM mechanism [17]

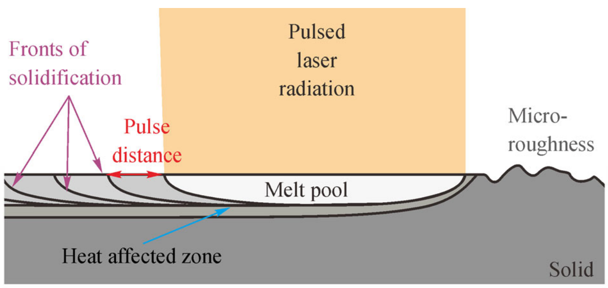

Fig. 5 Laser polishing using pulsed radiation [23]

surfaces of any orientation without the requirement for concealing, without the utilization of abrasives or fluids, without producing debris, and with negligible heat input to the substrate. Willenborg [2] pointed out that shorter laser pulse durations transcendently influence shorter wavelength features. Pulsed laser polishing enables better control of the melt depth and heat affected zone while still smoothing the surface. Perry et al. [5] showed that the first pulse from the laser always had high power when the laser was operated at high pulse rate (kHz). A mark would remain as a result of this at the point where the first pulse is incident on the surface. This mark can be fixed as a reference point to know the start point of the trajectory during an experiment. By using first shot suppression mode, the first pulse upshot can be reduced or avoided.

4.2 Continuous wave laser polishing

Continuous wave lasers are mainly used for macro surfaces. In continuous wave lasers the polishing process would be continuous as these types of lasers produce continuous beams rather than discrete beams. The melt pool for re-melting process is not only affected by the laser beam diameter and the average laser power but also by the scanning velocity. Usually continuous wave lasers are used in the case of surfaces having Ra of 2–16 μm. Milled, turned or electro-discharge machining-processed surfaces can be polished with the help of a continuous wave laser along with a re-melting depth of 20–200 μm [24]. A roughness rate of Ra = 0.1 μm can be achieved with the help of this type of polishing. Commonly continuous wave lasers of power output between 70 and 300 W is used for polishing process. Since continuous wave lasers have more power, the chance of producing heat affected zones would be more than pulsed lasers [25]. These types of beams can penetrate at a high processing speed. For example, a 500 W multi-mode laser can provide 0.508 mm penetration at 127 mm/s.

Past work by Wang et al. [26] showed that fused quartz machined surfaces could be cleaned from 2 to 0.05 mm (i.e., peak-to-valley distance) by using a 25 W CO_2 continuous wave laser raster examining. The cleaning instrument for this situation is softening of a micron size layer of material streaming under the activity of surface tension. The subsequent surface was a mirror smooth, polished film with no change in surface geometry. Wang et al. [26] performed two tests, the first test carried out with 32 and 40 W laser and the second with various laser powers and angles. Same laser power with different scan speeds are obtained in the two tests. The low energy density did not provide enough heat to increase the surface temperature for smoothening of the surface in Test 1. The viscous flow was not sufficient as the energy density was less due to larger laser beam size [26].

When used continuous wave polishing process, a better surface is obtained as it reduces the overlap distance and thereby avoiding the beam lines on metal surface after polishing. In certain specific applications the beam needs to be defocused in order to avoid these beam lines which appear on metal surface. While doing continuous wave polishing the sample surface can be placed either on top, below or at the beam focus [16,27].

However, with a continuously polished surface, a surface roughness of Ra = 0.05 μm is obtained [26]. Therefore, it was concluded that overlapping of laser beams are needed for continuous polishing as beam energy density is non-uniformly distributed. Continuous wave lasers produce high power output, which makes it suitable for polishing of most of the metals such as copper, nickel, steel, brass, silver, and gold. These lasers emit a constant single beam which can be considered as one of the benefits of using this type of laser, but if the purpose of polishing is to polish a surface which needs specific incisions which are of complex shape then pulsed lasers are highly preferred [28]. Continuous wave laser polishing can be utilized to polish metals and alloys without detectable changes to its mechanical or metallurgical characteristics. Specifically, there was no confirmation of thermal cracks after laser polishing [29].

4.3 Combination of pulsed and continuous wave polishing

The combination of pulsed and continuous wave laser is mainly done with the help of installing a Q-Switch. Temmler et al. [30] have analyzed the surface of metal by polishing using both pulsed and continous wave beams. In the experiment, first continous wave laser beams are used to re-melt the metal surface so that the surface gets smoothened significantly and due to the material flow within the melt pool the inhomogenity within the re-melted surface are homogenized. The first step in the experiment used continous wave beams to do laser polishing. In the second step, laser power and scanning velocity are varied systematically with pulsed laser beams. A spatial roughness spectrum analysis is done as shown in Fig. 6 [23].

It is observed that the white color isopleths indicate that roughness is reduced, and black color isopleths indicate that roughness is increased after macro polishing. By changing the power and scanning velocities, micro roughness is reduced. Thus, it is concluded from the experiment that macro roughness stays virtually unaffected for all scanning velocities and power less than 70 W. If micro roughness is to be minimized a laser power of 30–50 W is generally preferred [23]. Studies depicted that both continuous and pulsed waves have its own specific applications.

The combination of continuous wave lasers and pulsed wave lasers can produce a much smoother surface as compared with those produced with only one type of beam [31]. Temmler et al. [30] from his experiment showed that using both type of lasers the smoothness rate can be increased considerably. It is shown that a dual gloss effect is produced with the combination of these two types of lasers when used one after the other. The space resolved variations of surface roughness is given as the reason for the dual gloss effect. This application paves the path for generation of a new idea called selective laser polishing.

4.4 Selective laser polishing

The intense use of lasers in the industrial applications, such as in medicine, communication, manufacturing, automobile, and optics, has led to an increase in demand for a new technology for surface smoothening in the manufacturing industry. Polishing of selective areas of high precision was one of the increased demands among the manufacturers in the industrial sector [32]. Conventional polishing methods, such as abrasive blasting and mechanical polishing, are not able to do the polishing of precision components which needs selective parts to be polished [32]. Selective laser polishing is a variant of laser polishing where locally defined areas are re-melted as shown in Fig. 7 [23]. This process can be done using both continuous wave and pulsed laser beams where a dual gloss effect can be achieved. The treatment in the primary direction of

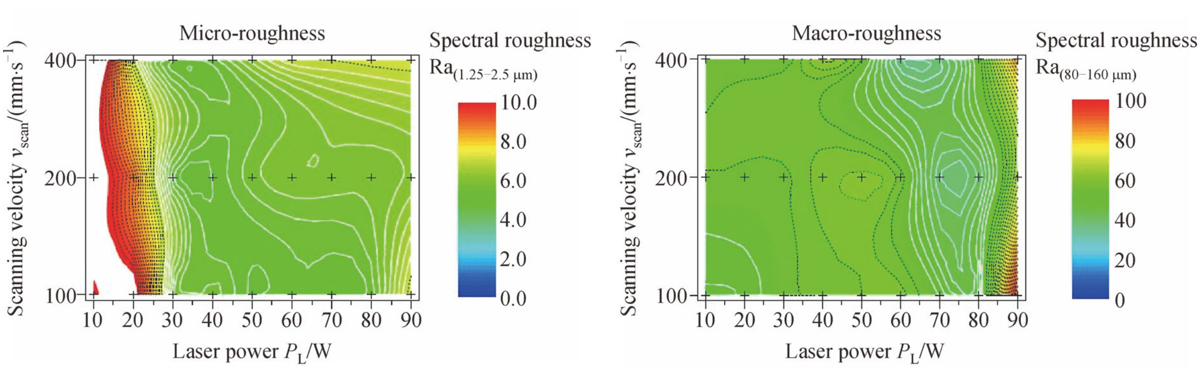

Fig. 6 Spectral roughness in dependence on laser power and scanning velocity as a miscoloured isoplethic diagram for micro- and macro-roughness for combined polishing with continuous wave and pulsed laser radiation [23]

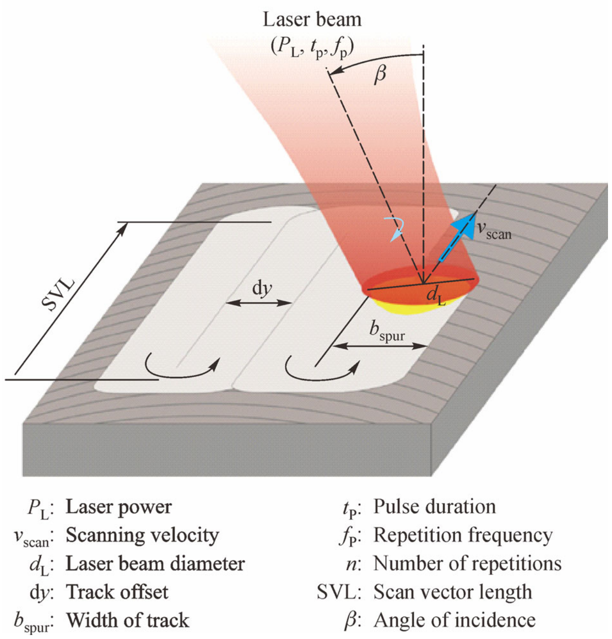

Fig. 7 Laser beam incident on metal surface on particular area [23]

processing is done with a scanning velocity v_{scan}, while the velocity in the secondary direction (v_{sec}) of processing can be calculated using Eq. (1) [23].

$$v_{sec} = v_{scan} dy/(x + dy), \quad (1)$$

where v_{scan} is the scanning velocity, v_{sec} is the processing velocity in the secondary direction, dy is the track offset, and x is the scan vector length.

At defined places (x,y) the laser power is modulated rectangular between a base level, where no treatment takes place and a processing level, where the laser power is sufficient to re-melt the surface [23]. Therefore, only defined areas of the surface get smoothed and a dual-gloss effect can be created.

As per the work done by Lamikiz et al. [31] in 2007, the selective laser sintering (SLS) reduction of surface up to three times of mean surface roughness is achieved. However, Kumstel and Kirsch [24] in 2013 studied the laser polishing of sintered titanium and nickel-based alloys. According to their work, the polished surface mainly depends on the laser beam density, initial topography of material and surface material.

5 Laser beam propagation

Laser beam is an electromagnetic wave which has a unique direction, which when interacts with metal surface it can be regarded as an electromagnetic interaction process [33,34]. In case of a plane wave, when focused the beam to a specific point results in a focal point. When a laser beam of a certain power is focused on focal point, the cross section of beam would go to zero which gives the intensity an infinity value. Since the laser beam cannot have an intensity infinity this would not practically work for a real laser beam. For more clear idea, in Fig. 8 [35] the spatial distribution diagram is shown for an experiment which is conducted with laser to analyze the beam profile at two different modes. The laser when placed at a point and keeping a film in front of laser, the laser spot gives cross section or area of focus of beam in that film. When the beam is allowed to pass through a lens and keeping the film at back of lens the cross section of laser beam is large and as the film moves further the cross section or area of beam reduces up to a certain point and then it again starts increasing its area. Thus, it can be experimentally shown that the area of focus would not go to a zero value rather the beam converges and starts to diverge again from a certain point. When analyzed carefully the beam profile of lasers looks like a bell-shaped distribution called the Gaussian distribution. It is known Gaussian beam because the intensity distribution over the direction perpendicular

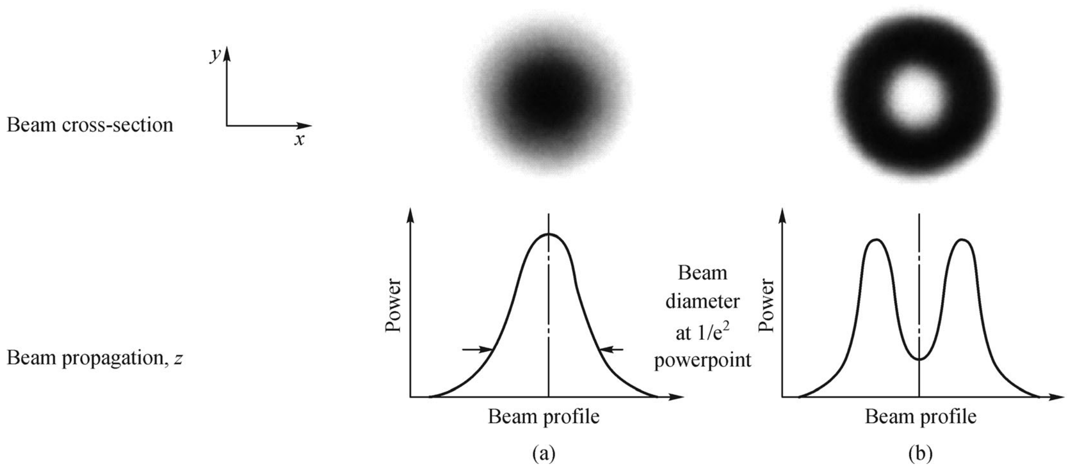

Fig. 8 Spatial intensity distribution modes for (a) TEM_{00} and (b) TEM_{01} [35]

to the axis of propagation is a Gaussian beam profile [36]. When the beam is in TEM_{00} it gives a Gaussian beam profile. The most favorable focusing condition can be found out using a Gaussian beam profile.

Liu [37] proposed a simple technique to measure the spot sizes of a pulsed Gaussian beam surface. A direct image of the laser energy density distribution is obtained on the crystal surface which was based on an optically induced phase transformation on single-crystal silicon surface. While conducting experiments using lasers in polishing process, mainly three surfaces are considered to hold the workpiece—ON surface, top of surface and bottom of surface. The distribution varies according to these positions where we hold the work piece. In certain cases, the beam needs to be defocused so as to get a larger diameter and less intensity. In this situation it is better to keep the workpiece below the surface which gives more distance between the workpiece and the laser. The Gaussian beam profile usually comes in a diverging manner from the laser and then converges at the center and then again diverges, thus giving a bell-shaped curve.

Also, for certain applications the beam needs to be distributed equally. In this condition a phenomenon called beam shaping can be introduced. Beam shaping is the process of redistribution of the irradiance of the laser beam [38]. In most of the industrial applications beam shaping is important as various applications need a preferred beam shape. By the manipulation of output powers, it is possible to get controllable beam shaping for the output intensity profile. The experiment proving this concept is shown by Litvin et al. [39] in 2017.

6 Process development

Laser polishing is a process by which only a thin microscopic layer of material is removed from the top of the metal surface. No material is removed as a result of this process. The fast re-solidification of melted metal from the peak to valley depends on various process parameters. The layer which melts should remove the roughness peaks. For this to happen, the temperature should have the potential to melt the peaks, but it should not be able to go deeper than valleys. As discussed in the previous section, the process mainly depends on three factors: The surface material, initial topography, and the energy density of the laser beam. Various studies [40,41] showed that if the process parameters are controlled accurately and precisely moving the stage results in high surface finish. The features such as laser energy density, wavelength, pulse duration, angle of incidence, scanning speed, scanning method, and characters of tested material affect the finally polished surface [5,42,43]. To be more specific laser polishing process is a thermodynamic-based process where mainly three categories of parameters plays pivotal role in the material interaction region of laser beam with the metal surface.

1) Workpiece: Initial topography of the material which includes dimension, surface roughness, homogeneity of surface, and other thermal and optical parameters.

2) Laser optics related parameters such as laser power, pulse duration, pulse frequency, beam diameter, beam shape, focus offset, and beam intensity.

3) Motion related process parameters such as tool path trajectory, number of overlaps, percentage of overlap, and feed velocity.

The interaction time between the laser and the metal surface depends mainly on the laser scanning speed for both continuous as well as pulsed laser beams.

6.1 Energy density

The process of polishing would be successful if the energy density is chosen accurately [31]. Energy density plays a crucial role in the thermal cycle, fluid dynamics, micro structure and the surface profile while it is delivered to the workpiece [44]. If the energy is stored in a given system or a particular region of space per unit volume it can be termed as energy density. In case of laser polishing process, energy density means the ratio of laser power to scan speed and beam diameter [18]. As per previous work, the reduction of surface roughness up to 37% of original Ra can be achieved if the energy density is properly controlled [18]. While performing a laser micro polishing process, the constant control of a laser energy density is the key technology to improve the surface roughness [8]. The energy density depends on the laser power, beam diameter and the interaction time of beam with the surface of the work piece. The energy per unit surface has a much higher heat when compared to that of a plasma arc. In case of a pulsed laser beam, the time of interaction is directly the pulse duration but in case of a continuous beam laser the energy density is inversely proportional to the feed rate. The energy density (ED) can be calculated as [31,45]

$$\mathrm{ED} = \frac{6000P}{Dv_{\mathrm{f}}}, \tag{2}$$

where P is the power of laser (unit: W), D is the diameter of the beam (unit: mm), and v_{f} is the beam feed rate (unit: mm/min) and the value of ED is obtained in J/cm^2.

The metal surface polishing using a CO_2 Laser, it is observed that a reduction rate ranging between 75% and 85% is obtained. From Fig. 9 [15], Ukar et al. [15] noted that a maximum roughness reduction rate is observed for energy density value ranging between 1800 and 3000 J/cm^2.

6.2 Pulse duration

Pulse duration in laser polishing is a term which is obtained as a result of the ratio of pulse energy to peak powers.

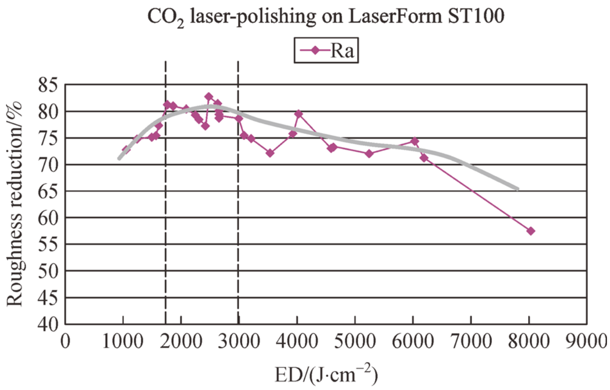

Fig. 9 Relation between roughness reduction and energy density [15]

Usually measured in nanosecond (ns) or micro second (μs). Pulse duration is also a process parameter which has an important role in obtaining a smoothness which is desired. Nüsser et al. [46] in 2011 showed that shorter pulse duration produces lower micro roughness ($\lambda = 5$ μm). The experiment was conducted using a disk laser and a rod laser of wavelength $\lambda = 1030$ nm and $\lambda = 1064$ nm, respectively. It is observed that the difference of surface roughness achieved is lower for disk laser than for that of the rod laser because of the lower relative difference of the pulse duration. This experiment also proved that the longer the pulse duration, maximal spatial wavelength is the outcome [46].

The simulation results from another experiment showed that longer pulse durations create a much smoother surface than obtained from shorter pulse duration [12]. Researchers in most of their researches used pulse duration in a common range between 200 and 650 ns. Micro fabricated nickel samples which had an initial surface roughness of Ra = 0.175 and 0.112 μm is reduced to 0.026 and 0.015 μm respectively by controlling the pulse durations [11,47]. When polishing process is carried out with a 300 ns pulse duration, it showed only 30% surface roughness reduction [12]. Figures 10 and 11 [12] show graphs obtained with 300 ns pulse duration and 600 ns pulse durations

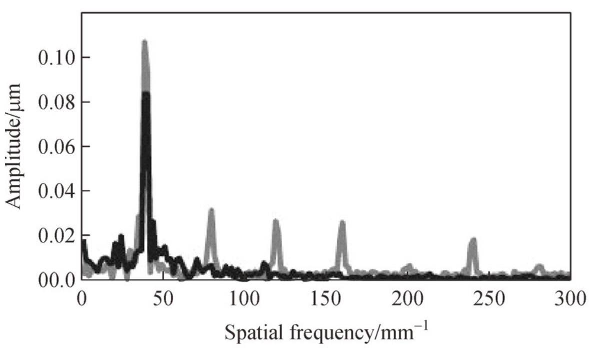

Fig. 10 Spatial frequency plot using 300 ns pulse duration [12]

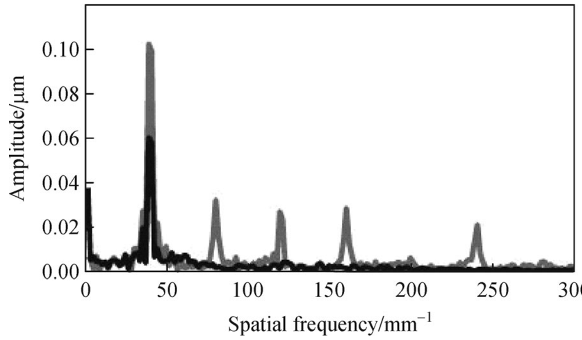

Fig. 11 Spatial frequency plot using 600 ns pulse duration [12]

respectively which clearly indicates that longer pulse durations provide better surface smoothness.

In Figs. 10 and 11, the black line represents the polished region and unpolished region is represented with the grey lines. Therefore, it can be observed that higher the wavelength (spatial frequency) shorter would be the damping duration.

6.3 Feed rate

Many researchers studied the effect of feed rate on the final metal surfaces obtained after polishing. Feed rate in lasers means pulses per millimeter. The peaks on the metal surfaces are removed using the laser irradiation where an improper speed can result in a rough surface instead of a smoother one [48]. Previous works showed that higher feed rates above a certain limit lead to a rougher surface and poor surface finish which is evident from Fig. 12 [48]. It is seen that the surface roughness decreases until feed rate = 300 mm/min and above that point the roughness again starts increasing. It is evident that low feed rate gives severe melting along with sporadic contraction during the coagulation process.

6.4 Laser beam overlap

During laser polishing activities, polished territories are commonly created by progressions of parallel laser beam tracks showing a specific level of overlap between them. The overlap level of the successive tracks represents an imperative procedure parameter. Moreover, unlike machining, tiny overlaps are also not desired in laser polishing, since they cannot change the underlying surface profile significantly. They are also regularly actuated with higher estimations of surface roughness. If the overlap is high, it results in uneven surface, bulging, and other surface damages [49]. This happens because of the reason that when the laser beam overlaps the successive beam the heat developed on the surface would exceed the required amount and thus it leads to damage of mechanical properties and surface integrity. It is seen that surface

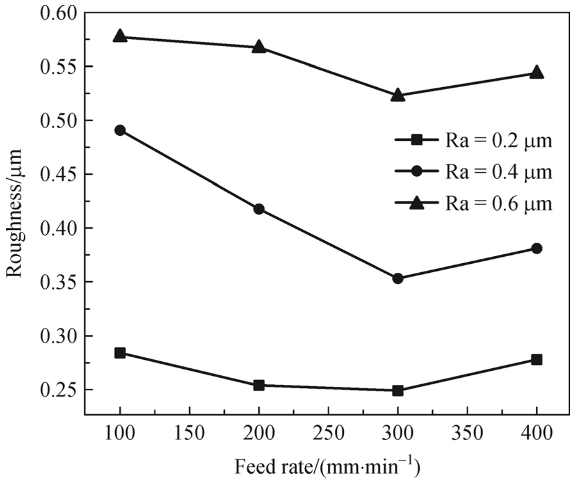

Fig. 12 Relation between surface roughness and feed rate [48]

quality is improved at a 95% overlap of beams and is decreased when it reaches 97.5% overlap. The improvement in surface roughness is calculated as [49]

$$\text{Improvement in surface quality} = [(\text{Ra}^{\text{initial}} - \text{Ra}^{\text{polished}})/\text{Ra}^{\text{initial}}] \times 100\%, \quad (3)$$

where $\text{Ra}^{\text{initial}}$ represents the initial roughness of the surface, and $\text{Ra}^{\text{polished}}$ represents the polished surface roughness.

The effect of beam overlaps on the material ratio function of initial and polished surface as it increases in overlap percentage is shown in Fig. 13 [49]. It is observed that laser polishing process not only helps in the reduction of peak-to-valley distance but also improves the micro geometry of the surface that is reflected by a reduced slope in the middle of the straight line [49].

Based on all the process parameters discussed above there are two regions developed as a result which are discussed in the next section.

6.5 Residence time and scanning speed

Residence time is the time of interaction between laser beam and work piece which can be calculated with the following equation:

$$R = \frac{\tau \cdot \text{PRF} \cdot d_s}{U}, \quad (4)$$

where R is the residence time (unit: s), τ is the pulse width (unit: s), PRF is pulse repetition frequency (unit: s^{-1}), d_s is the spot diameter, and U is the beam scanning speed.

Scanning speed is the relative speed between metal surface and laser beam. Scanning speed when increased less energy is absorbed as time gap will be reduced.

6.6 Focal offset distance

The amount of energy delivered to metal surface can be controlled by varying the focal offset distance (FOD). Focal distance is the relative distance between the focal

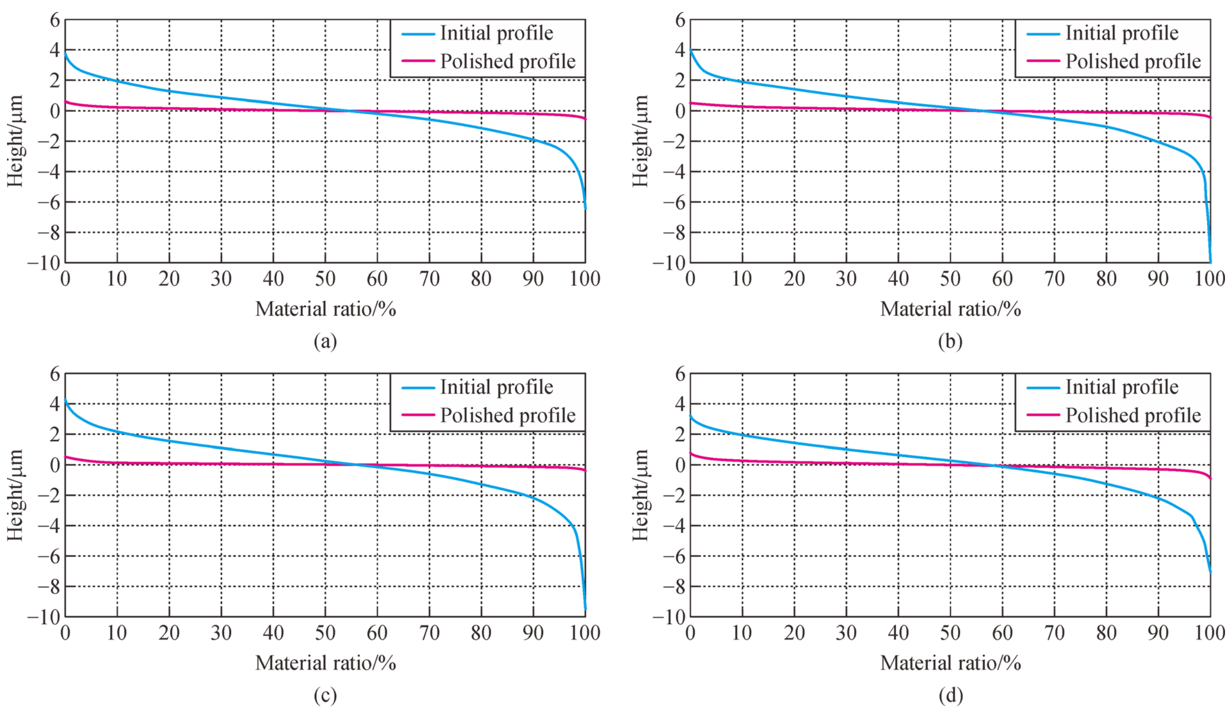

Fig. 13 Effect of overlap on material ratio functions of initial and polished surface [49]. (a) Sample 1 (80% overlap); (b) Sample 2 (90% overlap); (c) Sample 3 (95% overlap); (d) Sample 4 (97.5% overlap)

point of the laser and the sample. By adjusting the focal distance, it is possible to control the energy of beam incoming. It is shown experimentally that varying FOD gives better control over the surface smoothness [50]. As a follow up, Chang et al. [51] have given a much clearer idea about the effect of FOD on surface quality of steel components. As per his spatial frequency analysis, it is found that a drop in FOD decreases the highest peaks on the steel surface. From Fig. 14 [50] it is easy to understand the focal distance and FOD and they differ from each other. There should be a minimum of 1 mm FOD provided in order to allow the expansion of material, to safely allow passage of fumes and for less oxidation effect [52–55].

When compared the initial topography of metals with the laser polished surface various researchers [18,23,26] found drastic change. In spite of faster polishing rate, it also gave high quality surfaces. Experimental results mainly depend on the comparison with calculation of parameters of initial and final polished surface.

When H13 tool steel with initial line profiling roughness of 1.21 μm after laser polished reduced its line profiling roughness to a minimum of 0.040 μm as shown in Table 2. The results obtained by Hafiz et al. [49] are shown in Fig. 15.

7 Surface roughness

7.1 Analysis and measurement of surface roughness

The size of melt pool is one of the most important factors in determining the final surface roughness of the metal surface. Previously surface roughness was measured using surface profile measuring instruments such as profilometer. The contact between the probe tip and the workpiece surface would give the surface roughness. But while the probe moves over the metal surface it is possible to develop scratches on the surface which can vary the entire surface roughness value. This proves to be a major disadvantage of using profilometers. As time passed, modern technologies such as 3D optical microscopes were able to measure the surface roughness accurately than the conventional profilometers. Various methods for measurement of coordinates of the micro structures were discussed with a micro-coordinate measuring machines (CMM) having a micro probe [7]. An instrument called Fizeau interferometer can be used to measure the multi degree of freedom of a surface that is movable. This technique can be incorporated into the polishing process in order to find out the deviation of a movable surface which is the table where

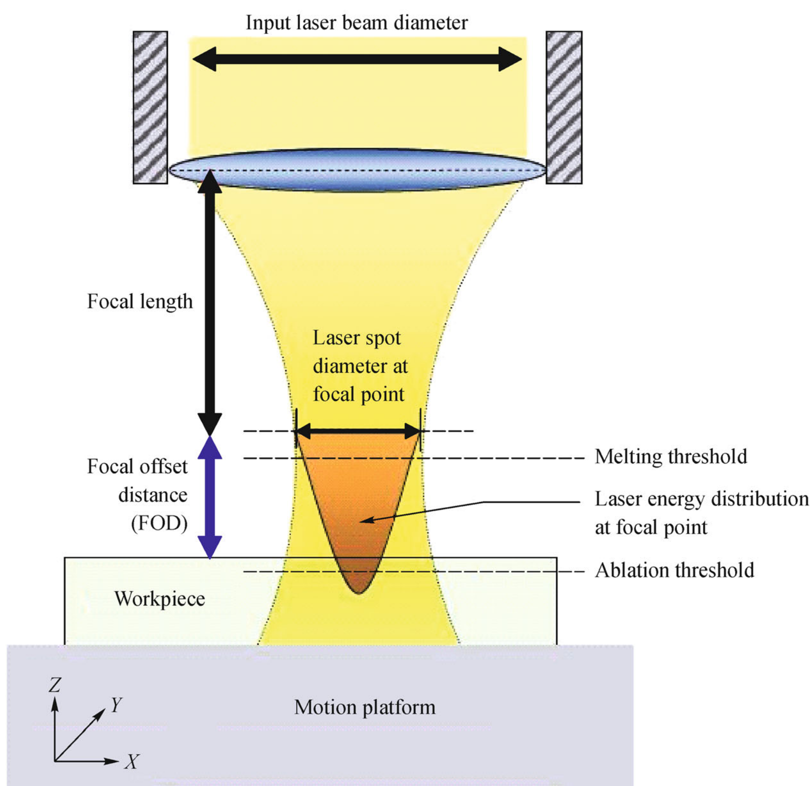

Fig. 14 Focal offset distance [50]

Table 2 Initial vs. final roughness comparison using laser polishing on H13 tool steel [28]

Overlap percentage	Initial line profiling roughness/μm	Polished line profiling roughness/μm
80.0%	1.18	0.19
90.0%	1.16	0.16
95.0%	1.21	0.13
97.5%	1.21	0.04

the workpiece will be fixed with respect to a surface that is not movable. The surface roughness can be measured mathematically using Eq. (5) [56]:

$$\mathrm{Ra}=\frac{1}{N}\sum_{n=1}^{N}|rn|, \tag{5}$$

where N is the total number of experiments performed and r is the roughness value at each experiment. Gloor et al. [57] performed an experiment using ultraviolet lasers on diamond surface where he used a profilometer to detect the improvement of average surface roughness. In order to get a more accurate measurement of the average surface roughness value, he used an atomic force microscope (AFM). In nano level, AFM is preferred over surface profilometers as it comparatively gives very high spatial resolution. Recent works of metallic surfaces have been reported by Hafiz et al. [10,54] and Şimşek et al. [58].

For a closer analysis of the surface structure, a scanning electron microscope (SEM) can be used. Using SEM, higher resolution images of surface can be obtained after laser polishing and thereby it is possible to analyze the effects of melting and surface roughness. As per Sato et al. [59], other than the higher resolution, it is not possible to measure the surface roughness directly using SEM. Surface roughness is an important term in medical field as in modern society the usage of medical implants is increased.

Figure 16 [60] shows the SEM image of polished DF2 (AISI 01) steel surface from which it is possible to see the gaps between melts. The surface roughness can be seen as smooth when compared with the surface that are seen through the gaps between melts. It is mentioned that the change in surface structure has a high influence on surface roughness. The measurement of these roughness is important to analyze the surface structures as well. Surface roughness occurs when the grain structure is non-homogeneous along with other inhomogeneities which are already present in the material [61]. Surface roughness measurement is also influenced by several factors by which the measurement value differs which is discussed in detail in next section.

7.2 Factors affecting surface roughness

The surface roughness of a workpiece after a laser polishing process is affected by numerous factors. From the previous works done by many researchers in the area of laser polishing and the effects of different lasers (CO_2, excimer, diode, fiber) on the metal surfaces many factors have been identified which affect the final result of the surface roughness.

1) Initial surface roughness of the metal to be polished is one of the major factors as different location in the metal have various roughness rates. Notably the lateral dimensions of the surface structures should be known.

2) Homogeneity of the material also proves to be a factor that affects the surface roughness. If the surface does not possess similar characteristic properties it may result in poor surface finish as the laser beam hits the entire surface with same power and intensity. Thus, segregations and inclusions may occur which may downgrade the quality of the surface.

3) The thermos-physical material properties such as heat conductivity, viscosity, surface tension, melting, and evaporating temperature affect the roughness of the surface.

4) The influence of process parameters such as beam diameter, its intensity and the time of interaction of laser beam with the metal surface also influence the final surface smoothness. If the laser beam has higher intensity rate, the temperature developed would be high. If the temperature rises above the melting point of the metal, it results in an

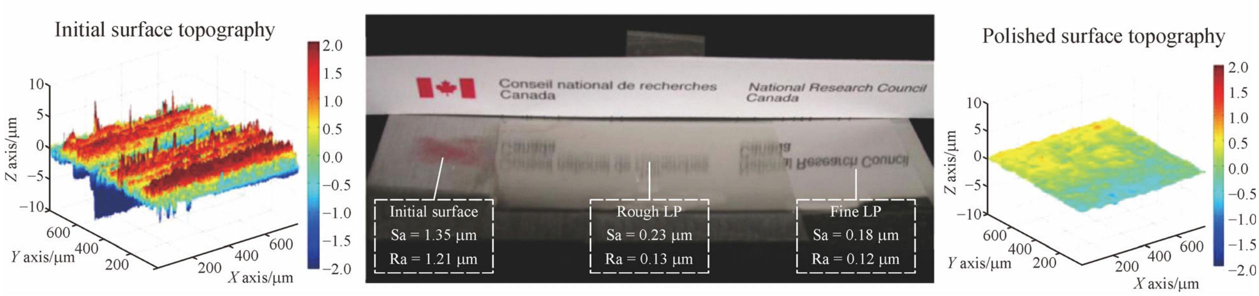

Fig. 15 Initial and polished surface profile of H13 steel with Sa and Ra values [49]

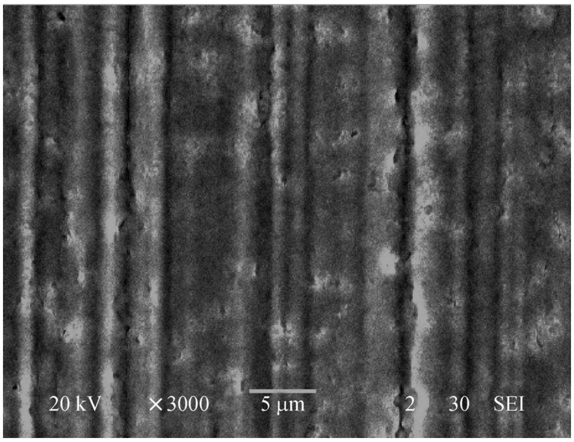

Fig. 16 SEM image of laser polished DF2 (AISI 01) steel surface [60]

entire melt pool leading to a SOM region. The longer the interaction time and the intensity of the beam the lower will be the roughness of the surface.

5) Depends on the time taken by the laser to process a metal surface. Usually a processing time of 1–10 s/cm^2 is used.

8 Advantages of laser polishing

The need for polishing has been rocketed in the past ten years due to the increasing needs for the fast-developing society as shown in Table 3 [8,31,51,62–66]. There is a magical rise in the need for highly precise components in each and every sector including medical and industrial. Since its invention in 1960 [67–69], laser has laid its mark in almost every industrial sector for different applications. The polishing using lasers are now trending as the increased need for the precise and highly smooth surface. Most of the developed countries have made large amount of investments in their laser research programs. But most of the science projects would be having limited funding which proves as a motivation for further developments in this area making use of the available less budgets [70].

Laser polishing is widely used in various applications in different areas such as in dental, bone implants, light weight design of porous structures due to its unlimited flexibility in polishing small areas (<1 mm^2), and complex parts. Laser polishing is used to get a high glossy surface finish [21,71,72]. It is a fully automated machining process which delivers a wide range of advantages. Some

Table 3 Overview of the recent development in laser polishing

Author	Time horizon	Number of papers reviewed	Type of laser used	Proposed theory
Lamikiz et al. [31]	1995–2006	16	CO_2 & Nd:Yag Laser	A method for surface finish for the parts made using SLS method where 80.1% surface reduction is achieved
Jang et al. [8]	N/A	14	UV Pulsed Laser	A technique for stability of laser energy density in the laser micro-polishing using UV pulse laser on the material surface [8]
Pfefferkorn et al. [62]	N/A	16	200 W Fiber Laser	A two-pass process is introduced where the first pass thermocapillary flow is made use to reduce the surface roughness whereas in the second pass the unconsumed process features are discarded
Brinksmeier et al. [63]	1927–2003	9	Nd:Yag Laser (wavelength 1064 nm)	Polishing of V grooves (structured steel and electroless nickel plated steel molds) done by abrasive polishing, laser polishing and abrasive flow machining
Martan et al. [64]	N/A	19	Nanosecond pulsed laser (KrF excimer laser with wavelength 248 nm and pulse duration 27 ns)	Using the combination of a two-reflection based system, a surface temperature measurement system is developed
Rosa et al. [65]	1997–2014	15	Fiber laser (800 W power and 1070 nm wavelength)	Focused on laser polishing of ALM surfaces along with an experimental investigation to hone ALM surfaces based on laser polishing strategies and parameters.
Bhaduri et al. [66]	N/A	52	MOPA-based ytterbium-doped fiber nanosecond (ns) laser (50 W power and 1060 nm wavelength)	Analysis of the oxidation on metal surface using X-ray photoelectron spectroscopy and glow discharge optical emission spectroscopy. A surface reduction rate of 94% is obtained using laser polishing
Chang et al. [51]	N/A	34	Micro second ytterbium-doped single-mode fiber laser (20–500 W varying power and 1060 nm wavelength)	Proposed that the melting zone and heat affected zone thickness can be expressed as function of deposited energy. Also, when the polishing process carried out in argon atmosphere there are no evidence of crack formation

Note: UV: Ultraviolet; ALM: Additive layered manufacturing; MOPA: Master-oscillator power amplifier of the major advantages due to use of laser for the process of polishing is discussed below:

✤Lasers deliver beam size which can be even concentrated on specific areas. Thus, the polishing of selective regions is possible with the help of laser polishing (< 1 mm^2).

✤The processing speeds are high when compared to conventional polishing methods. The processing speed depends upon the intensity of the beam and type of material to be polished.

✤Polishing of various surfaces such as milled, eroded, turned, and ground surfaces can be polished using laser polishing.

✤No environmental damage such as pollution or grinding and polishing wastes occur after laser polishing process.

✤There is no requirement for a skilled labor to carry out the entire polishing process as the entire process is fully automated.

✤When compared with conventional polishing techniques such as mechanical, electro chemical, hydrodynamic, and magnetorheological polishing, laser polishing enhances the appearance of the surfaces way better by adding much more glossy effects which cannot be achieved with the help of old polishing techniques.

Each type of lasers has its own advantages in the process of polishing. For instance, CO_2 lasers are mainly used in the polishing of general applications such as plastics and glass, whereas fiber lasers are used for specific applications such as in metals.

While polishing the coating thickness is a major factor for the improvement of the surface quality of the layer which is coated. Thus, conventional methods of polishing fail in this aspect whereas laser polishing helps in the improvement of surface quality by perpetuating the thickness of the coating [73]. Another expediency of laser polishing includes high reproducibility and low mechanical stress on components since it is a non-contact process. Also, there is no need for any extra addition of polishing or grinding agents while carrying out the polishing operation. Using very less processing time even complex geometries of metal parts can be polished using this technique. This process can be implemented on commercial SLS machine [74].

For the metal deposition applications in the past few years, a number of technologies have been emerged, namely, SLS [75], laser engineered net shaping [76] and selective laser melting [77]. These rapid manufacturing processes allowed the fabrication of complex parts but the major challenge for this type of process is that it produces surfaces with poor surface quality [78]. Laser polishing proves as an alternative for this snag which is evident from the experimental results given by Lamikiz et al. in 2007 [31]. Results showed that using laser polishing process Ra = 1 μm is obtained on SLS parts which had an initial roughness rate of Ra = 8 μm. Likewise, it is said that polishing can take even more than 30% of the total manufacturing time [35]. In this case, laser polishing also stands out from the box as processing time of parts is much less which reduces the overall manufacturing time.

When coming on to the specific type of lasers, there are mainly three types of lasers used in the industry: Nd:Yag laser, CO_2 laser, and fiber laser. Fiber lasers can be regarded as the ideal successor of the Nd:Yag laser since fiber lasers have higher reliability, duration of operation, beam quality, and are highly efficient. But when it comes to CO_2 lasers it has a different scenario as it has a completely different absorption co-efficient when compared with wavelength of fiber laser. On analyzing the case of glass polishing, CO_2 lasers have an advantage over fiber laser as the laser beam directly goes through the glass in fiber lasers whereas it is absorbed by the glass when CO_2 lasers are in operation. This is due to the 10 times longer wavelength of the CO_2 lasers as compared with fiber lasers. But in case of metals, a low power CO_2 laser cannot be used since the beams will get reflected when incident on metal surface. However, fiber lasers are most commonly used nowadays for the polishing of metals due to their beam quality and efficiency.

Conventional automated polishing leads to problems such as edge rounding and unprocessed areas because shafts which are deeper are not processed [79]. Also, this makes polishing of freeform surfaces difficult. In primordial times, these kinds of freeform surfaces were manually polished. But with the pioneering of laser polishing technique the polishing of freeform surfaces become easier.

9 Challenges in laser polishing

Despite of the numerous perks discussed about the laser polishing process, there are various challenges associated with this process as well. The high initial cost of laser polishing is one of the major challenges faced by the process. A fully automated laser polishing machine cost above 500000 USD. The laser polishing machine includes a 5-axis CNC machine along with a scan head and gas chamber where the work piece to be polished is kept. An important aspect of using a gas chamber during polishing is to prevent the oxidation of metal surface during the polishing process. Atmosphere is a mixture of several gases and when the polishing process is carried out in the atmospheric condition the oxygen in the atmosphere gets combined with the metal surface. Thus, it can result in crack formation or irregularities in surface after polishing [51].

The diffraction limit of the laser beam is one of the other major challenge indulged with laser polishing process. When the diffraction limit is less the resolution of the beam hitting on the metal surface will be less. Thus, in order to polish metal surface more beams would be needed where in turn it results in high power consumption rate. Using

Eq. (6) [15] the minimum spot beam diameter can be calculated if the laser wavelength and refractive index is known.

$$d = \frac{\lambda}{2n\sin\alpha}, \tag{6}$$

where d is the minimum spot diameter, λ is laser wavelength, n is the refractive index of the beam to the material, and α is the beam divergence angle. While analyzing the various scenarios the most difficult parameter to control is spot size, since it depends not only on the laser itself but also on FOD. Manufacturers set the spot size and energy distribution for the focal point for each laser type and lens, but in some applications the laser beam is defocused in order to obtain a larger spot. In laser polishing the laser beam can be defocused for higher productivity or to vary the energy distribution, producing spot size variation. Also, it has been observed in previous works that, as the initial surface roughness decreases the laser-polishing process is less effective. In other words, the better the initial surface finish, the lower the polishing rates for the laser process. One experiment used Ti-6Al-4V sample [29] which is used as a test material because of its challenges with laser process such as surface cracking and rapid oxidation [80]. The relation showing the spot size with the FOD is shown in Fig. 17 [15].

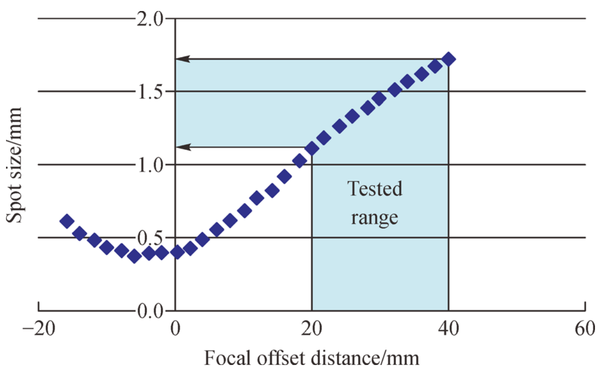

Fig. 17 Relation between spot size and focal offset distance [15]

From Fig. 17 it can be seen that when the focal offset values of 20 to 40 mm are set, spot diameters of 1.12 to 1.72 mm are obtained. This is done by defocusing the CO_2 laser beam which is used in the experiment done by Ukar et al. in 2010 [15]. The main aim of the experiment done by Ukar et al. [15] was to obtain a much lower mean surface roughness (Ra) with apex beam diameter and feed rate.

Alternately, it depends on the energy density of the laser beam as well. For a minimum value of energy density melting of the surface does not happen whereas for maximum value it emanates in SOM regime [15]. It is difficult to control the phase change, i.e., from solid to liquid phase. Many numerical models were developed to solve the non-linear moving boundary problem of this phase change which is called as Stefan problem [81]. An experiment conducted on glass to minimize the thermal stress developed resulted in a failure as the surface of the BK-7 glass cracked very badly when heated in an oven to analyse the effect of thermal stress [82]. Even though the BK-7 glass (amorphous) has lower expansion co-efficient [35] with low temperature the stress developed is tremendous due to the high temperature caused as a result of the laser fire polishing [82]. Cracks are formed on the surface of glass. Thus, it is clear that glasses with lower expansion co-efficient can be polished by using laser beams whereas the glasses with higher expansion co-efficient cannot be laser polished.

Laser polishing is a result of the solid-liquid phase changes, therefore authors have proposed that this model could be possibly derived from the classical problem of moving phased boundary, which is also known as Stefan problem. Numerical models/techniques have been developed for the simulation of ephemeral laser melting process [81]. Lasers which are available currently are those with an optical wavelength ranging from 248 nm to 10.6 μm with high power [83]. Therefore, the procurement of nano scale ($\leqslant$100 nm) resolution remains still an obstacle. Even though ultra-precision machining process are of high interest among industrial sector the measurement of nano scale structures still remains as a barrier. Fang et al. [84] explained both contact and non-contact measurement of surface profile in nano-metric scale in which currently CMMs are most commonly used in the contact measurement for freeform surfaces whereas interferometry and CMM with autofocus sensor mounted with laser probe is used for non-contact measurement process. A major challenge faced by industry is in the surface finish of these freeform optical surface. Some of the key challenges in the metal structures while doing laser polishing are discussed below:

✤Larger area polishing (at least 4 in wafer size);
✤Greater operating distance ($>$1 mm);
✤Good surface finish;
✤Removal of debris;
✤Higher production rate;
✤Lower cost;
✤Greater precise size control of process parameters such as beam diameter and intensity of beam;
✤Oxidation of metal surface when polishing carried out in atmosphere;
✤The polishing of initially smoothened surfaces.

Fundamental studies are required to discern how material grain structures affect the laser polishing and final surfaces obtained after polishing. There is still a scientific challenge prevailing which is how a laser beam radiation affects the nano-material properties and structures. Using the technique of self-perfection by liquefaction it is shown that nano-material can be polished using an excimer laser [85]. The polishing of NIL (nanoimprint lithography) molds with very small feature size is esoteric

[86]. One other challenge while doing laser polishing in nano-materials is the sealing of nano-channels. It is a strenuous process as the channels become clogged. The reason for this is that the soft materials can be smoothly compressed into the channel. Therefore, while doing the polishing process the molten material can flow into this channel and thereby causing blockage of the channels. In addition to this, development of cracks can also be a threat on the metal surface due to the mis-match in the thermal expansion between the substrate and the material.

The effect of residual stress formation and compressive stress formation is studied by Preußner et al. [86]. He stated that the residual stress formation is the result of tensile force and the compressive stress formation is due to transformation stress. Residual stress moves from tensile to compressive stress with the increase in laser beam diameter or the laser power and also from number of repetitions of re-melted workpieces [86]. Residual stresses are developed when large rates of heating or cooling occur in a sample. Residual stress is highly influenced by the process parameters. On the other hand, it is observed that larger wavelength such as 3 mm and if the beam diameter and power is also high which results in compressive stress. Development of compressive stress occurs when the surface is re-melted multiple times [86].

However, there are many strategies to control the surface topology during laser polishing. As per the investigation done by Marimuthu et al. [29], who used a numerical model based on computational fluid dynamic formulation it is found that input thermal energy is the key parameter that affect the melt pool convection and controls the surface quality.

10 Applications

Lasers have been used for a wide range of applications such as welding, cutting, engraving, soldering, drilling, micro machining, ablation and deposition, marking, etching, and curing [69,87]. Micro or nano scale surface polishing is of high interest in the industrial sectors. Fang et al. [7] proposed machining of various complex surfaces on nano scale such as textures on curved surfaces where laser polishing can be implemented to improve the surface quality. Manufacturing of freeform optics and its applications in medical and industrial sectors are clearly mentioned by Fang et al. [84], where he pointed out various key challenges and suggested possible ways to avoid them.

Laser polishing emerged as a disruptive innovation which is now widely used for a medley of applications mainly in medical and industrial purposes.

10.1 Industrial applications

To obtain more efficiency of the overall equipment highly polished surfaces of individual components with high precision rates are desirable. For this reason, laser polishing comes top on the priority list. Achieving a highly smooth surface without any surface defects. A wide range of materials such as ceramics [88], metals such as steel [63,89], titanium alloys [5,24], and nickel [12]. To compete with rest of the world, the European companies were forced to switch on to new emerging technologies such as laser polishing which helps in the additive layered manufacturing process [90]. By incorporating laser polishing this process can be achieved at a faster rate since the processing time of the material surface is less as compared with other polishing processes. Both pulsed and continuous wave lasers are used in industries for the surface smoothening process. In LCD (liquid crystal display) manufacturing industries, the laser-controlled fracture techniques are now commonly used for the flat glass separation [91]. A general trend of using excimer lasers can be seen in industries for polishing of ceramic materials [92]. Mostly titanium and steels are preferred materials to be polished due to their low cost and reliability. Also, fiber lasers are the most preferred laser type used in industries due to their low cost, high efficiency, high beam quality, reliability, and can easily melt metal surfaces [93]. The polishing of freeform surface even though remains a challenge, it proves to be of high interest in industrial sector. For example, Fig. 18 [94] shows the initial and polished spherical surface. Laser polishing in the recent year has extended its application to the telecom sector for achieving a high gloss surface finish [94]. ‘Laser Polishing Ceramic Material’ was first patented in 2017 by Apple which was used in ceramic Apple watch for the first time [94]. The polishing of even hard materials makes laser polishing suitable for industrial applications.

Fig. 18 Laser polished spherical cap (on left) and initial surface (right) [94]

10.2 Medical applications

Fine polishing of biomedical devices, surgical instruments, and body implants have increased the demand to use lasers. The use of optical fiber in medical industry relies in prevalent applications such as in endoscopes, remote spectrometry devices and position sensing or scintillation counting, in sensors for medical audiometry [95]. In 2014, a feasibility study by Tsai et al. [96] was conducted on the polishing of optical fiber for removing the conical-end-faces in optical fibers. The surfaces of micro lens need to be highly polished to obtain the best quality. Another application of laser polishing is smoothening of inside regions such as microfluidic channels. Weigarten et al. [97] performed laser polishing of inner walls of micro fluidic channels of fused silica where ultra-short pulsed CO_2 laser beams of wavelength $\lambda = 10.6$ μm is used for this purpose due to the fact that fused silica has a low optical penetration depth (4–30 μm). In 2016, Jung et al. [98] showed the surface generated by grinding process in fused silica material if done laser polishing, will result in a better surface smoothness. Micro fluidic devices have promising applications for biological as well as chemical research and for increasing their efficiency laser polishing is adopted. Titanium and its alloys are also widely used in medical industries for a variety of applications such as in dental orthopaedic implant materials [99]. Excimer laser are used to polish medical implants made of titanium [100]. Along with all these laser polishing is adopted for getting a high gloss surface and to remove the sharp corners and edges in stents [101,102]. Moreover, heart pumping components such as in hub and hub cap are also nowadays using lasers to smoothen its surface as shown in Fig. 19 [103].

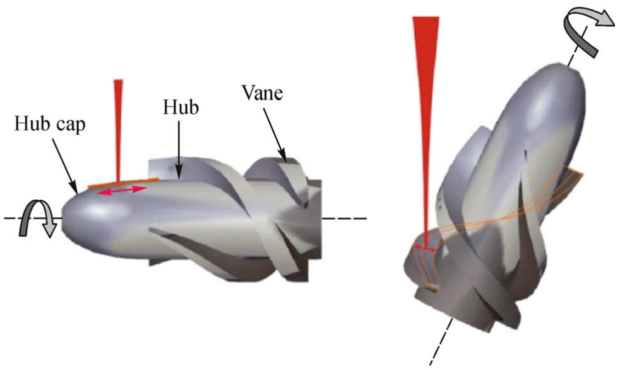

Fig. 19 Schematic diagram showing laser polishing of hub and hub cap [103]

The surface smoothening of medical implants and the components used in cardiac surgery such as ventricular assist devices is of increased demand [104]. In 1991, Buser et al. [105] studied the effects of titanium implants integration in bones. He found out that with the increase in surface roughness of the implants there is an increase in contact between bone and the implant. This can cause further damages inside our body due to the friction happening between the bone and implants. But other studies [106–108] failed to prove this explanation from Buser et al. [105].

10.3 Other applications

High-end sectors always need high precision equipment for various purposes such as in night vision devices. Along with these opto-electronic devices used in imaging areas and in aeronautic applications, individual components which requires highly polished surfaces undergo laser polishing [65]. CO_2 lasers have been widely used in many industry applications because of the ability of CO_2 lasers to perform polishing of glass effectively than fiber lasers. The sharp corners inside the optical fiber components used in military application is removed with the help of laser polishing. Polishing of glass surfaces can be mostly done using CO_2 lasers [109] which can be used in the night vision devices. Optical detectors polishing using CO_2 lasers have a great rate of interest in military. Şimşek et al. [58] showed that 20.4 and 4.07 nm surface roughness is achievable from an initial surface roughness of 30 and 9 μm.

11 Conclusions

Based on the review of various articles published, pulsed lasers are much more preferred considering economic feasibility as low power pulsed lasers can do the polishing process. The polishing process results in surface damage by the formation of cracks due to surface oxidation and carbonisation. If the laser parameters, such as energy density, spot diameter, beam intensity, are controlled accurately, a high gloss surface finish can be achieved using laser polishing. According to the laser power that has been used, the laser beam diameter can be adjusted. By using higher laser power, larger beams can be used which would cover more surface at one time, which would decrease polishing times greatly. However, usage of high laser power, larger scan velocity, and higher hatch distance can cause ripples on the machined surfaces. Many researchers are working on different sorts of materials, particularly on the laser polishing of various metals. The strategies which should be used for laser polishing along with the analysis of factors that have been known to influence the polishing must be studied more clearly.

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