11.3 Polishing with Laser Radiation

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The surface roughness of a part or product strongly influences its properties and functions. Among these can be counted abrasion and corrosion resistance, tribological properties, optical properties, haptics as well as the visual impression the customer desires. Therefore, in industrial manufacturing grinding and polishing techniques are widely used to reduce the roughness of surfaces.

A new method to attain such high-quality surfaces is polishing with laser radiation. In principle there are three different process variants [19]. At the top of Fig. 11.23 a sketch of a cross-section of a milled surface is shown. With *polishing by large-area ablation* material is ablated over the whole surface. Thereby, the smoothing is achieved by increased ablation of the peaks of the surface and decreased ablation in the valleys. In contrast, *polishing by localized ablation* requires a precise measurement device for measuring the initial surface profile. After a nominal/actual value comparison only the peaks of the profile are ablated by a controlled laser pattern. The third process variant is *polishing by remelting*. A thin surface layer is molten and the surface tension leads to a material flow from the peaks to the valleys. No material is removed but reallocated while molten. In the following, further details are shown for all three process variants [63].

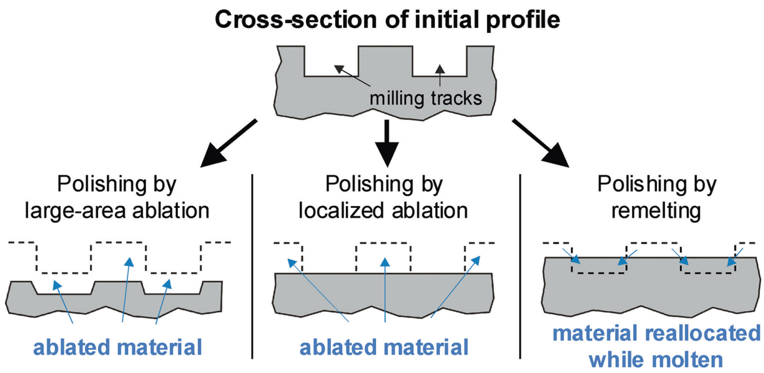

Fig. 11.23 Process variants of polishing with lasers

11.3.1 Polishing by Large-Area Ablation

Polishing by large-area ablation is predominantly used for CVD diamond films and plates [20–22]. For the most part, excimer lasers are used (ArF, KrF, XeCl). For thick

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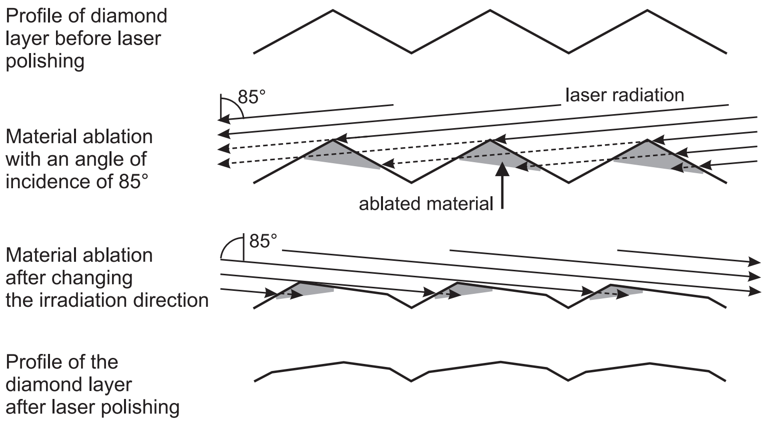

Fig. 11.24 Scheme of polishing of diamond films and plates with lasers

films and plates (> 100 μm) argon ion lasers, copper vapor lasers, and frequency-doubled Nd:YAG lasers are also suitable, often combined with a finishing step, again with an excimer laser. In order to ensure increased material removal at the profile peaks, laser polishing is carried out with an angle of incidence of up to 85° to the normal of the aimed surface (Fig. 11.24). A further reduction of the roughness can be achieved by rotating the sample during processing.

The roughness of thin films (< 100 μm) with initially $Ra = 0.1$–1 μm can be reduced by a factor of 2 to 4. For thick films with initially $Ra = 20$–30 μm, even higher reductions are possible. The processing time is between a few minutes up to several hours per square centimeter depending on the laser source, one or two step processing, and initial roughness.

11.3.2 Polishing by Localized Ablation

Polishing by localized ablation is based on the controlled ablation of profile peaks with pulsed laser radiation. To locate the position of the profile peaks, an elaborate and costly profile measurement system is required. The principle of this process variant is described in the patent specification [23], but no details are given concerning process parameters, achievable surface roughness and processing time. Polishing by localized ablation has not been investigated in much detail to date. In the industry localized ablation has been mainly used to structure surfaces for the manufacturing of micro tools.

11.3.3 Polishing by Remelting – Metals

Polishing of metals by remelting with laser radiation is a new method for the automatic polishing of 3D surfaces. The main characteristics are as follows [19]:

- A high level of automation.
- Short machining times especially in comparison to manual polishing.
- No pollutive impact from grinding and polishing wastes and chemicals.
- Polishing of grained and microstructured surfaces without damaging the structures.
- The generation of user-definable and localized surface roughness.
- No changing of the form of the workpieces. Deviations of the form are not corrected but otherwise an already perfect form is not damaged.
- Small micro roughness as the surface results from the liquid phase.

For metals for the process-variant polishing by remelting, two subvariants exist: macro polishing and micro polishing.

Macro polishing is carried out with cw laser radiation. Milled, turned, or EDM-processed surfaces with a roughness Ra up to several micrometers can be polished [24, 19, 25]. Remelting depths between 20 and 200 μm are used. Beam diameter and remelting depth have to be chosen according to the material and the initial surface roughness. Normally, fiber-coupled Nd:YAG lasers are used with laser powers of 70–300 W. The processing time is between 10 and 200 s/cm^2 depending on the initial surface roughness, the material and the desired roughness after laser polishing. The achievable roughness depends on several influencing variables [24]:

- Initial surface roughness and especially the lateral dimensions of the surface structures.
- Thermo-physical material properties, e.g., heat conductivity and capacity, absorption coefficient, viscosity, surface tension, and melting and evaporation temperature.
- Homogeneity of the material: segregations and inclusions especially downgrade the surface quality.
- Medium grain size and statistical distribution, a small grain size is preferable.

Theoretically, the surface tension smoothes the surface of the melt pool, and a "perfect smooth" surface should be achievable. But during the remelting and solidification process, several mechanisms produce new surface structures resulting in a process-induced roughness. Figure 11.25 shows the most important mechanisms. The challenge of laser polishing is to minimize the sum of these mechanisms. This can lead, however, to competitive objectives for the process parameters. The main field of application for macro polishing is the substitution of the time- and cost-consuming manual polishing, e.g., in tool and mold manufacturing.

In contrast to macro polishing, *micro polishing* is carried out with pulsed laser radiation [19, 27–31]. The pulse duration normally is in the range of 20–1000 ns and the remelting depth in the range of 0.5–5 μm. With the micro polishing process variant, only fine pre-processed surfaces (e.g., grinded, micro milled) can be polished. Due to the small remelting depth, larger surface structures remain unaffected and can, therefore, not be eliminated. The most important process parameters are pulse duration and intensity. Longer pulses can eliminate laterally larger surface structures. The intensity has to be chosen according to the pulse duration and the

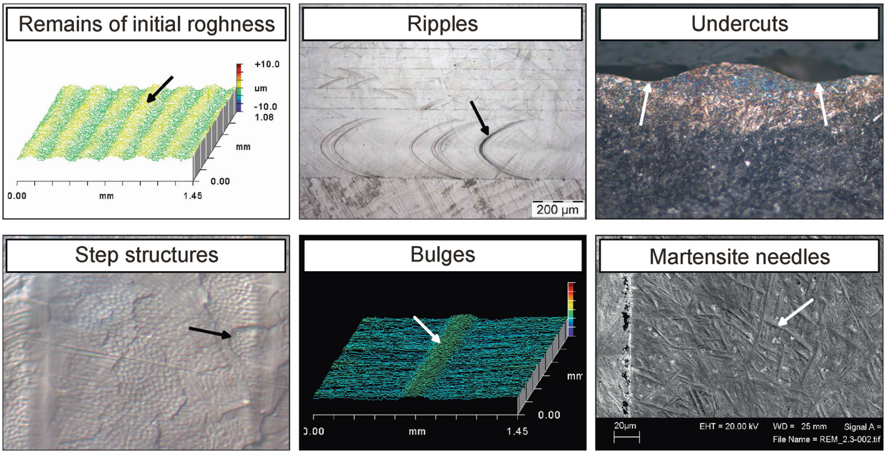

Fig. 11.25 Structures preventing a "perfect smooth" surface after laser polishing [24, 26]

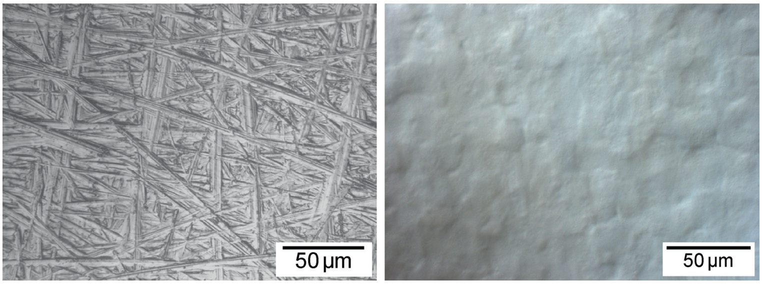

Fig. 11.26 TiAl6V4 surface milled (*left*) and micro polished (*right*)

material to be polished. A top-hat intensity distribution is preferable to generate a homogenous remelting depth. Fiber-coupled Nd:YAG and excimer lasers are used. Processing times less than 3 s/cm^2 can be achieved. Figure 11.26 shows a TiAl6V4 surface before (left) and after micro polishing (right). Due to the fine micro roughness, micro polishing is especially suitable for tribological and medical applications. Furthermore, the localized polishing and adjustment of the gloss level allows the generation of design surfaces [32].

The micro polishing process variant is limited to smooth surface structures with lateral dimensions of up to 40 µm. Larger surface structures can only be removed with the macro polishing process. But, in contrast to the macro polishing process, the micro polishing process often leads to a finer micro roughness and, therefore, to a higher gloss level. As a consequence for some applications, a combination of both variants is used: first macro polishing to eliminate the tracks from milling or turning, then micro polishing to enhance the gloss level.

Figure 11.27 shows a glass form before and after laser polishing. The processing of 3D surfaces is still under investigation, but this example already shows that laser polishing can be applicable even for free form surfaces [64].

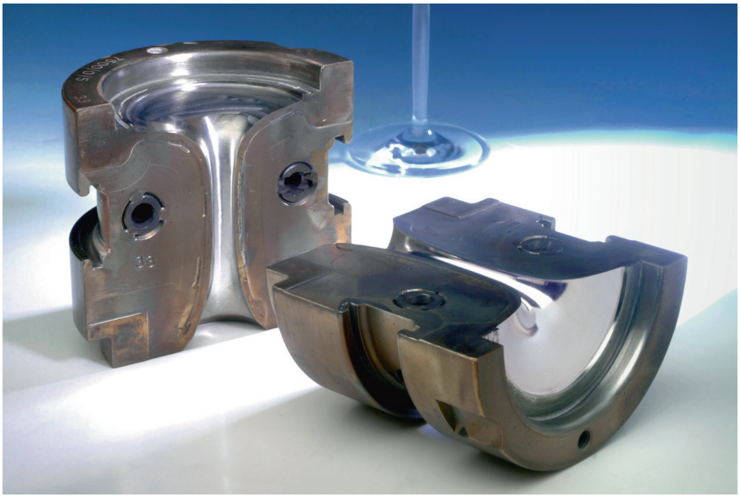

Fig. 11.27 Glass form for the manufacturing of shafts and feet of wine glasses grinded (*left*) and laser polished (*front*) [24]

Examples for polishing results are shown in Table 11.2. Copper, gold, and aluminium alloys show hitherto predominantly unsatisfying results, but otherwise laser polishing of these metals has not yet been investigated as closely as the polishing of steels and titanium alloys has.

Table 11.2 Polishing results for selected metals [19, 24]

Metal	Subvariant	Initial roughness, Ra (μm)	Roughness after laser polishing Ra (μm)	Processing time (s/cm^2)
Tool steels, e.g., 1.2343, 1.2344, 1.2316, 1.2365	Macro	1–4	0.07–0.15	60–180
1.3344	Micro	0.5–1	0.3	3
Titanium, TiAl6V4	Macro	3	0.5	10
	Micro	0.3–0.5	0.1	3
Bronze	Macro	10	1	10
Stainless steel 1.4435, 1.4571	Macro	1–3	0.2–1	60–120

11.3.4 Polishing by Remelting – Glass

Laser polishing of glass by remelting is similar to the conventional and widely used fire polishing with manual or automatic guided burners. But as a laser can be controlled more precisely than a flame, laser polishing allows higher surface qualities. Due to the high absorption coefficient, cw CO_2 lasers with a wavelength

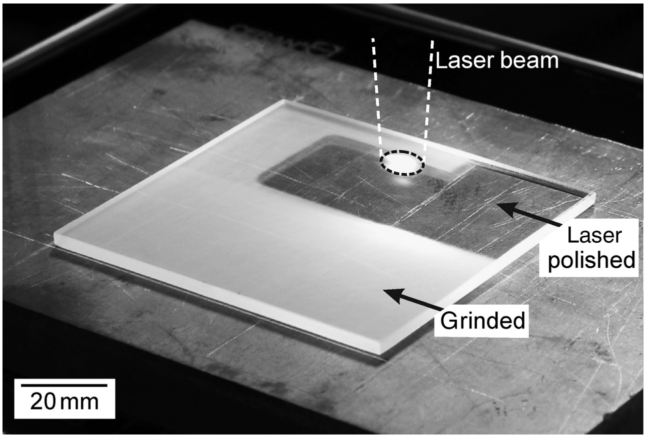

Fig. 11.28 Polishing of fused silica with CO_2 laser radiation [33]

of $\lambda = 10.6\,\mu m$ are used (Fig. 11.28). With the laser radiation the surface of the glass is heated. Evaporation has to be avoided, because otherwise material would be removed and a dent would occur. But the temperature must also be high enough to reduce the viscosity of the glass sufficiently in order to allow effective material flow from the peaks to the valleys. So the surface should be heated slightly below evaporation temperature.

The most important process parameters are the interaction time and the intensity. The longer the interaction time, the lower the roughness after laser polishing and the required intensity, but the higher the processing time. Usually, the laser power is between 30 and 4000 W, the intensity on the workpiece between 70 and 500 W/cm^2 and the feed rate between 2 and 80 mm/s [33–39]. Typical processing times are 1–10 s/cm^2. To avoid cracks preheating may be necessary, especially for glass with high thermal expansion coefficients. For preheating various heating devices or ovens can be used. For good polishing results, homogeneous preheating is a prerequisite.

In particular the micro roughness is smoothed. This and the avoidance of polishing lubricants can lead to the reduction of scattering losses of optics as well as to the enhancement of the destruction threshold. Form correction of optics through polishing by remelting has not been investigated yet. Examples for polishing results are shown in Table 11.3.

Table 11.3 Polishing results for different glass types [34, 33, 36, 38, 39]

Glass type	Initial roughness	Roughness after laser polishing
Lead glass	$R_z = 13.3\,\mu m$	$R_z = 2.5\,\mu m$
Fused silica	$R_{max} = 2\,\mu m$	$R_{max} = 50\,nm$
	$R_a = 150\,nm$	$R_a = 10\,nm$
TRC-33	$R_q = 500\,nm$	$R_q = 1\,nm$

11.3.5 Polishing by Remelting – Thermoplastics

Polishing of thermoplastics by remelting is similar to the polishing of glass. The main differences result from the lower process temperatures needed as a result of the low melting temperatures of thermoplastics. With a CO_2 laser with 500 W laser power, processing times less than 0.1 s/cm^2 are possible. Thermosetting plastics cannot be polished by remelting due to the lack of a liquid phase.

11.3.6 Summary of the Three Process Variants

Most common are the process variants polishing by large-area ablation and polishing by remelting. Polishing by localized ablation has only been slightly investigated. Table 11.4 shows a rough comparison of the three process variants. Polishing by remelting is divided into the subvariants, micro and macro polishing.

Table 11.4 Comparison of the process variants for laser polishing

	Polishing by large-area ablation	Polishing by localized ablation	Polishing by remelting	
			Micro	Macro
Materials	CVD diamond	Metals	Titanium, steel, nickel, cast iron	Titanium, steel, cast iron, glass, thermoplastics
Initial surfaces	Crystal structure from CVD process	n/a	Grinded, diamond milled	Milled, turned, EDM
Processing time	Minutes to hours per square centimeter	n/a	1–10 s/cm^2	0.5–3 min/cm^2
Laser sources	Excimer lasers and frequency converted Nd:YAG lasers	Pulsed lasers with nanosecond or subnanosecond pulse duration	Fiber-coupled Q-switch Nd:YAG lasers or excimer lasers with 20 ns to 1 µs pulse duration	Fiber-coupled cw Nd:YAG lasers for metals and cw CO_2 lasers for glass
Required machinery precision	Medium	High	Low	Medium
Achievable roughness	Strongly dependent on the material and initial surface roughness (see text)			
Special features	Flat angle of incidence required	Elaborate and costly profile measurement system required	Very homogeneous materials required	Homogeneous materials required

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