Laser Polishing of Silica Rods

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Abstract

Lasers have been widely used in surface modification. In this research a CO_2 continuous wave laser has been used to polish the slot surface of the silica rods. The strong absorption of the 10.6 μm CO_2 radiation by the silica surface promotes the softening of a very thin layer of material that flows under the action of surface tension. As a result, a mirror smooth glassy surface has been formed which decreases the surface roughness without any substantial change in the surface geometries. The effect of laser to surface inclination angle on the requisite power requirement was assessed experimentally and theoretically. With laser beam scanning controlled by a computer-aided design (CAD) database without specific tooling or human intervention, reliability and reproducibility of this process have been greatly improved compared to conventional fire polishing. The potential use of laser polishing as a post-processing step for freeform-fabricated parts is very promising.

Introduction

Lasers have been widely used in surface modification. The properties of a surface layer of a metal or semiconductor are modified by changing its composition or microstructures using focused radiant energy. Laser-driven heating processes can also be used to enhance the resistance of crystal and glass surfaces to laser damage[1,2]. Recently, laser beams have been used to polish glass in the optics industry[3]. It has been suggested that preheating the bulk to a point above glass transformation temperature before starting the laser-driven surface heating process can help avoid the generation of undersiable thermal stress.

Surface finish is a critical and, for some applications, limiting feature of parts produced using Solid Freeform Fabrication (SFF). Selective laser sintering (SLS) uses a laser and scanning system, so the possibility of laser polishing SFF parts is a logical approach to surface finish improvement. It is most desirable to present the laser to a part without regard to part geometry specifics. That is, the most robust laser polishing process would not require "on the fly" changes in laser parameters such as laser power or the inclination of the laser onto the part surface. The purpose of this investigation was to assess the feasibility of laser polishing of a part with simple surface features and constant initial surface roughness. Specially, we have chosen a silica rod with slots mechanically cut into the periphery.

A conventional polishing process is fire polishing, which requires technicians to sweep a hand-torch over the silica slots. This process can smooth the edges of the slots, but because of the relatively narrow space between adjacent slots, about 0.07 inch wide, fire polishing cannot polish the inside surface. Obtaining reliable and reproducible surfaces by fire polishing is difficult because the process is highly dependent on the skill and technique of the technicians.

The disadvantages related to fire polishing are effectively overcome by irradiating the slot surface with a laser beam as discussed in this paper. The results of this work are directly applicable to surface finishing of freeform-fabricated parts produced both from silica and from other materials amenable to laser surface polishing.

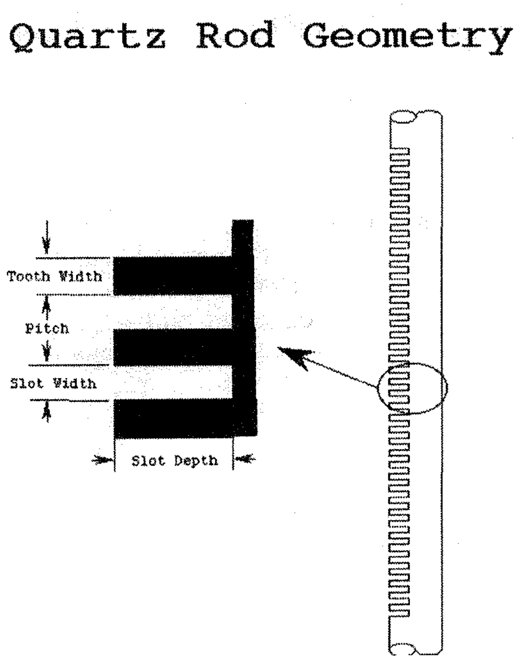
This work was done at the laboratory of SFF at University of Texas at Austin, where the SFF approach was first invented, originally conceived as a shortcut to making models and prototype parts. Solid Freeform Fabrication is now expanding its potential applications into short-run production, mold/die manufacturing, and smart laser processing.

CO_2 Processing Apparatus

Mechanically cut silica rod slots were used during the experiments. The geometry of the silica rods is shown in Figure 1. The silica slots were cut normal to the rod surface. The material was fused quartz, which is an amorphous phase of silica.

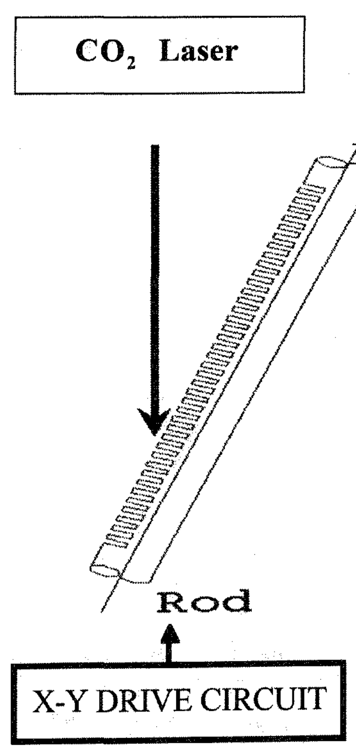
The absorptance of 10.6 μm radiation is about 80% for quartz[4], which is one of the crystalline state of silica. This is a high level of absorption. There is no available absorptance data for fused quartz. Since the wavelength of CO_2 radiation is much longer than the wavelength of the absorption edge of fused quartz, fused quartz has very strong absorption of the 10.6 μm radiation also[2,3]. Fused silica does not reflect CO_2 laser significantly[4].

In Figure 2, a schematic drawing of the laser polishing process is shown. A CO_2 continuous wave laser, with a maximum beam power of 50 W, was incident on the rod with angle ϕ after passing through the optical system. The inclination angle ϕ has been defined to be the angle (in degrees) between laser beam and the normal to the slot surfaces. ϕ can be changed to accommodate different slot geometries. For this work, the silica rods were moved by a motor in the X-Y plane, and the angle ϕ had been set up manually by geometrical measurement.



Diameter: 15 mm; Length: 50 cm
Tooth width: 0.07 inch; Slot width: 0.07 inch
Slot depth: 0.22 inch; Slots per rod: ~ 150

Figure 1. Schematic drawing of quartz rod



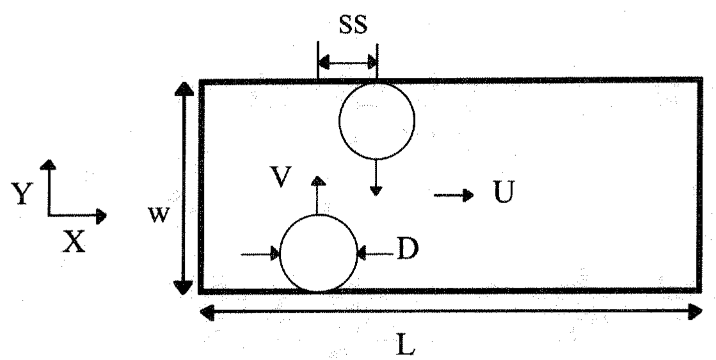
CO_2 Laser; ϕ: inclination angle

Figure 2. Schematic drawing of laser polishing

Experimental

To facilitate the effects of polishing, initially large, flat surfaces were made by bisecting silica rods using the same method as the slot cutting. Two sets of experiments were set up. Test I was carried out using 32 and 40 watt laser beam power on the bisecting surfaces with ϕ fixed at 0°. Test II was carried out using slot surfaces with various laser powers and angles, ϕ. The test results were studied by using Scanning Electron Microscopy (SEM), optical microscopy, a profilometer and a beamscanner.

Laser scanning for this work was a single-pass set up, which is shown in Figure 3. During this process, CO_2 laser radiation was incident on surfaces with different inclination angles, ϕ.



V: scan speed in Y, μm/S
U: scan speed in X, μm/S
SS: scan spacing, μm
D: laser beam diameter, μm
L: length of polishing surface, μm
W: width of polishing surface, μm
λ: overlapping, D/SS

Figure 3. Plan view of single pass polishing

Results and Discussion

Laser Beam Energy Distribution

In Table I, D was defined to be 50% cliplevel of the laser beam energy density E, which in theory should obey a Gaussian distribution as shown in Figure 4. By using a beamscanner, the beam energy distribution was recorded, which is shown in Figure 5. It has been found that the energy distribution for the CO_2 laser used in this work did not conform to the Gaussian form. In the X direction, E is uniformly distributed across the beam diameter. In the Y direction, the distribution was skewed. The energy distribution varied according to working conditions such as the laser cooling condition, power supply stability, beam power, etc. For simplicity, D was taken to be the 50% cliplevel of the Gaussian distribution in the Y direction for every laser power used in this work. E was taken to be uniformly distributed across the whole beam area.

Because of the non-uniform distribution of E, overlapping (λ) was introduced into this work to be the ratio of D and SS, to accommodate the lower energy density at the edge of the laser beam. The importance of λ will be discussed in detail later.

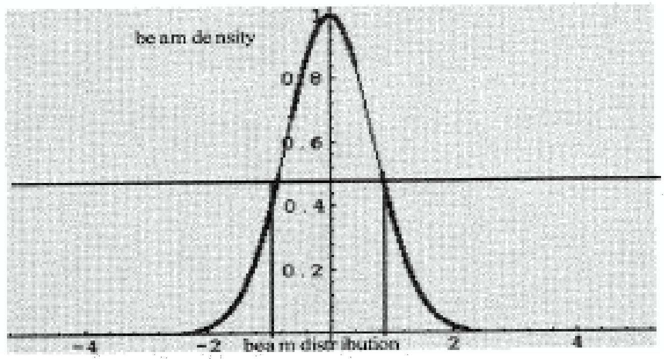


Figure 4. Gaussian distribution and 50% cliplevel for laser beam energy distribution
(Beam distribution for X axis is not based on this results)

Test	D (50%) (um)	scan spacing(um)	E(J/ cm**2)	λ (overlapphg)
Laser Polishing				
32 watts				
1	1000	50	408	20
2	1000	100	408	10
3	950	50	429	20
4	950	100	429	10
5	800	50	510	16
6	800	100	510	8
7	600	50	679	12
8	600	100	679	6
9	600	200	679	3
10	450	100	906	4.5
11	450	200	906	2.25
12	450	300	906	1.5
13	250	200	1631	1.25
14	250	300	1631	0.8
15	250	400	1631	0.6
16	200	400	2038	0.5
17	200	500	2038	0.25
40 watts				
1	1000	50	510	20
2	1000	100	510	10
3	950	100	536	9.5
4	950	200	536	4.75
5	800	100	637	8
6	800	200	637	4
7	800	300	637	2.67
8	600	300	849	2
9	600	400	849	1.5
10	600	500	849	1.2
11	600	600	849	1.0
12	600	800	849	0.75
13	450	400	1132	1.13
14	450	600	1132	0.75
15	250	300	2038	0.83
16	250	800	2038	0.31
17	200	800	2548	0.25

Table I. Different Experimental parameters for Test I and E (Energy density)

Test	Laser power	Inclination angle(degree)	Scan speed	Scan spacing(um)	Overlapping(λ)	Beam size(um)
1	11.8~30	0	1 cm/s	85	3	250
2	5.85~15	0	0.5 cm/s	85	3	250
3	13.5~33.75	30	1 cm/s	85	3	250
4	16.5~41,25	45	1 cm/s	85	3	250
5	8.33~20	45	0.5 cm/s	85	3	250
6	17~41	70	0.5 cm/s	85	3	250

Table II. Different Experimental parameters for Test II

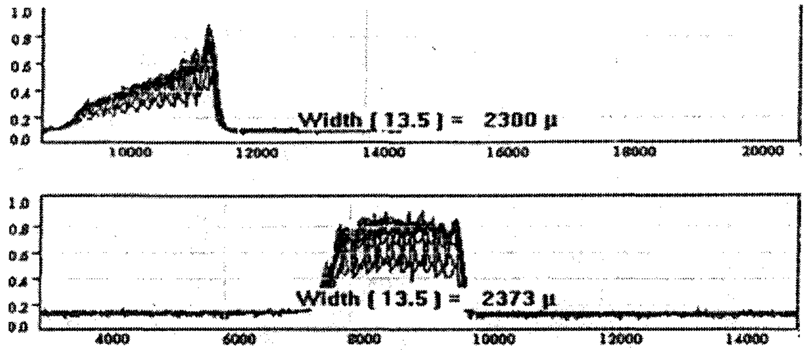


Figure 5. Beam profiles for 40 watt laser (Upper: Y direction; Lower: X direction)

Laser Polishing Working Window

The effects of a variety of important laser polishing parameters have been studied. These include laser power, beam diameter, scan speed, scan spacing and inclination angle ϕ.

The scan speed of the polishing process was restricted to be less than 1 cm/s. Laser beam diameter can be adjusted according to the laser power that has been used. By using higher laser power, larger beams can be used which will cover more surface at one time. This will decrease polishing times greatly.

From experiments, we found that there was a laser beam energy density range for polishing: the Laser Polishing Working Window. Too low a laser energy density didn't cause any obvious polishing for the slots. If too much laser power or slower scan speed was used, the surface was cut into grooves or covered by a layer of white powder. The grooves are shown in Figure 6.

(a) 32 watt ,Test I #14

(b) 40 watt, Test I #15

Figure 6. Grooves and cuttings on the polished surfaces

To smooth the slot surfaces, the surface temperature needs to reach the softening point of the material. Beyond that point a thin layer of material can flow under the action of the surface tension. If the laser energy is too low, the heat provided by the laser beam is not enough to raise the sample surface to the softening point where the viscous flow of silica can happen, and there is no smoothing effect.

At higher laser power or slower scan speed, SiO_2 evaporated from the irradiated region followed by decomposition. The resulting SiO can only exit as vapor phase. It redeposited as white loose particles of SiO_2 on the cooler parts of the sample.

$$2\ SiO_2 = 2\ SiO + O_2$$

This redeposition should be avoided by maintaining the slots surface temperature below the vaporization point. The depth of the damage increased with laser power density.

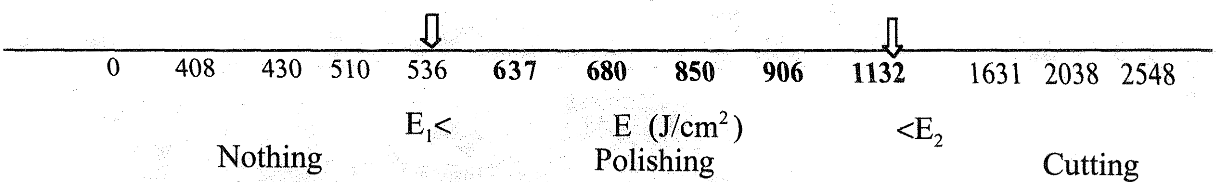


Figure 7. Laser Polishing Working Window for Test I

The results for Test I is shown in Figure 7. The working laser energy densities are from E_1 to E_2. The results for Test II are shown in Figure 8. The polishing windows have been shifted according to different inclination angles. Changes in the scan speed did not cause obvious deviations in these windows. The effect of surface roughness before polishing is not clear from this work.

Laser Beam Energy Density (E)

E for this work has been defined as following,

$$E = \frac{Pt}{A} \qquad (2)$$

Where P is the laser power (watt), t is the duration time of the laser beam on the surface at any given point and A is the area of laser beam (μm^2). By changing ϕ, beam shape changes from a circle with diameter D to an ellipse with D (semimajor axis) and D$\cos\phi$ (semiminor axis).

Substituting t, which is shown as following in Equation 3, and A into Equation 2, produces Equation 4,

$$t = \frac{D}{v} \quad (3) \qquad E = \frac{\pi D^2}{4\cos\phi} \quad (4)$$

Temple produced similar surface smoothing results [2], although for a different laser application. His laser beam energy was calculated out to be 796 J/cm^2 when using Equation 4. It is just inside the laser polishing density range from our work.

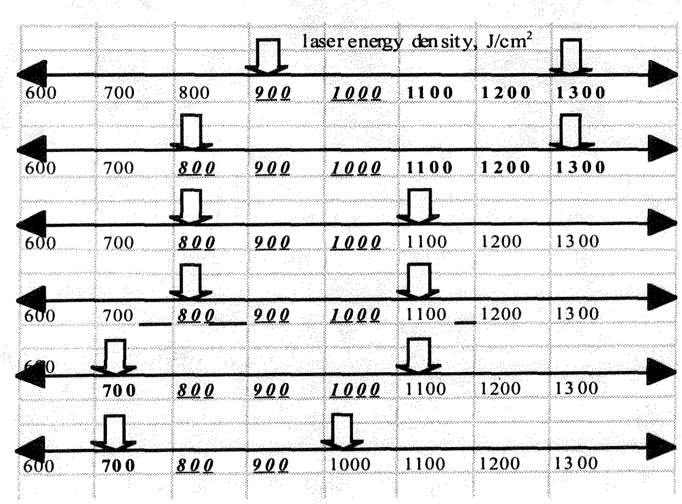


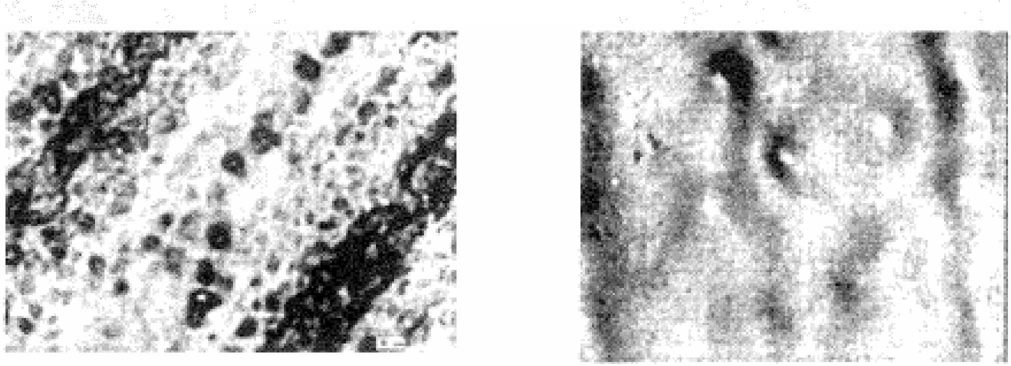
Figure 8. Polishing Working Windows of laser beam energy density for Test II
(Listed in the same order as Table II)

Surface Morphology

The surfaces profiles of silica slots before and after fire and laser polishing are shown in Figure 9. The as-cut surface is very rough with a lot loose particles adhering to it. After fire polishing, some of the loose particles have been removed and the surface roughness is improved. In comparison, laser polishing created a mirror-smooth surface without any loose particles sticking on it. There are distinct differences between the fire and laser polished surfaces. Laser polishing can guarantee the reproductivity and reliability by computer controlling the whole process.

Figure 10 shows the features of slot edges after different processes. Both fire and laser polishing can debur the edge without changing the feature of the egde. Although fire polishing can smooth the edge of the slot, it can not reach the inside because fire is blocked from entering into the narrow space between adjacent slots. By changing ϕ, laser beam can reach any point deep inside the slots, provided the laser has line-of-sight to all the areas of the surfaces. So, the surface inside the slot can be smoothed also as shown in Figure 10 (c).

Different overlapping had been used for Test I. Some results are shown in Figure 11. Surface (a) and (b) in Figure 11 both had the same laser power but different scan spacing. Between the polished areas, there was an unpolished space left in Figure 12(a). λ for both tests was greater than unity, which meant that beam overlapping occurred. But the lower energy density distributed at the brim of the laser beam did not provide enough heat to raise the surface temperature to the softening point of the materials. The larger laser beam size decreased the beam energy density also in Test I #12. So viscous flow was not sufficient for polishing.



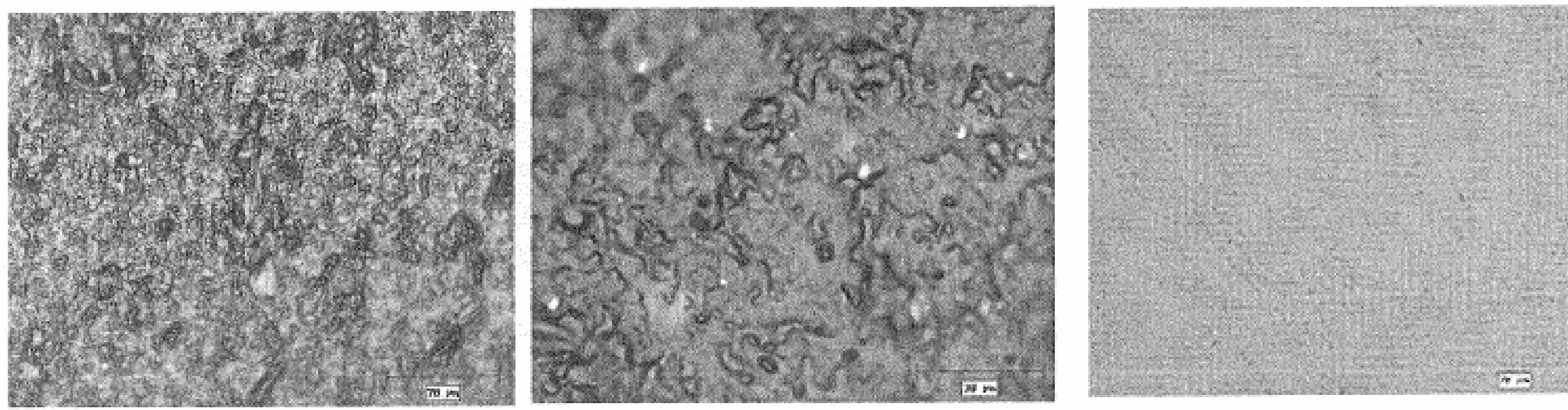
(a) partially polished surface, Test I # 12 (b) continuous polished surface, Test II, #4

Figure 11. Overlapping effect for polishing at 32 watt laser power

A surface profilometer was used to record the surface profiles for as-cut and after fire and laser polished slots. The results are shown in Figure 12. The surface roughness for an as cut surface is about 2μm for the peak to valley height. After fire polishing, it reduced to about 1μm. Laser polishing can reduce the surface roughness to 0.05μm.

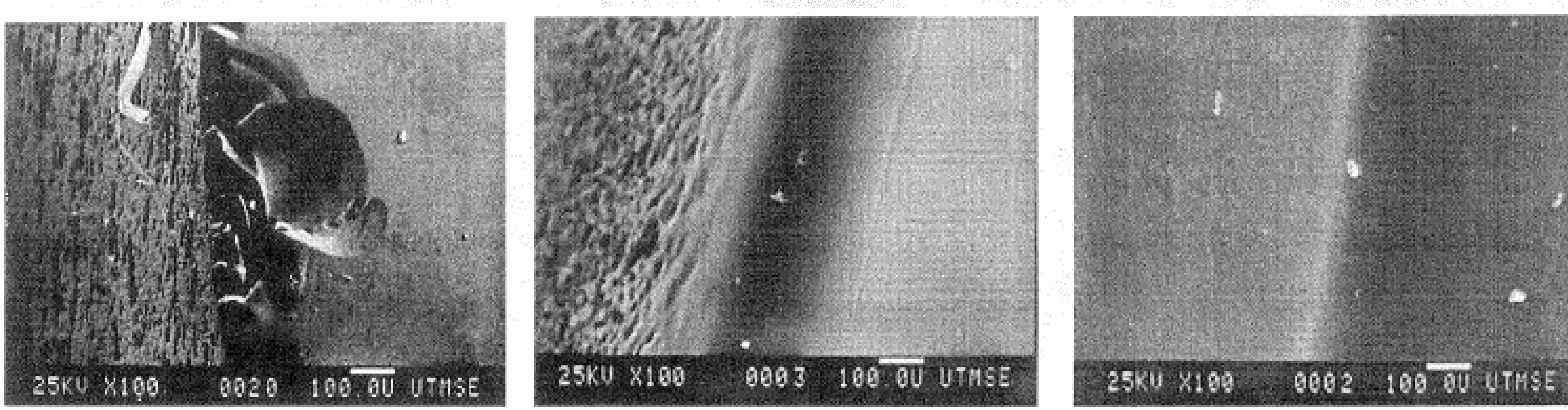
Summary and Conclusions

The materials studied for this project is amorphous silica, which does not exhibit a well-defined fusion phase transition. By absorbing laser energy, the surface temperature was raised to the softening point and the softened silica flowed under the action of surface tension and cooled before recrystalization could take place. The resulting surface was a mirror-smooth glassy film without any significant change in surface geometry.



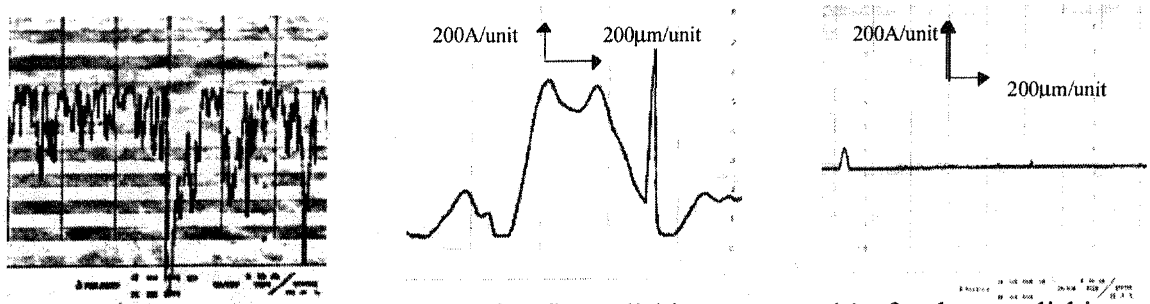
(a) surface as cut, 200x (b) surface after fire polishing, 200x (c) surface after laser polishing, 200x

Figure 9. Surface comparison for as cut, after fire and laser polishing (optical microscope)



(a) edge as cut, 200x (b) edge after fire polishing, 200x (c) edge after laser polishing, 200x

Figure 10. Edge comparison for as cut, after fire and laser polishing (SEM)



(a) as cut (b) after fire polishing (c) after laser polishing

[Plot (a) has the same X unit, but twice the unit in Y direction as in (b) and (c).]

Figure 12. Surface roughness profiles for as-cut and after-polished surfaces

Laser polishing process can potentially benefit a lot of materials. According to materials parameters such as absorptivity and reflectivity, different wavelengths can be chosen for laser polishing to provide the necessary energy.

We offer the following conclusions:
1. CO_2 laser polishing can create mirror-smooth surfaces on mechanically cut silica.
2. There is a laser polishing working window for silica surfaces. Below this power density range, there is no obvious surface roughness decrease; above this range, vaporization of SiO_2 to SiO occurred. SiO redeposited back on the surface producing a thin layer of white, loose particles of SiO_2 .
3. The pre-polished surface roughness affects the required laser beam energy density. The rougher the initial surface, the higher the required beam energy density.
4. Based on the physical properties (heat capacity, absorptivity, reflectivity, etc.) of the materials to be processed, different wavelength lasers can be chosen to provide the energy required for surface polishing.
5. Laser polishing can work on different surface geometries under the condition that laser has a line-of-sight to all areas that need to be polished.
6. Overlapping of laser beam was required for continuous surface polishing because of the non-uniform distribution of the beam energy density.
7. The potential use of laser polishing as a post-processing step fro freeform-fabricated parts is very promising.

Acknowledgment

The authors wish to thank Cryco Co., Austin, TX for funding this research.

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