Surface Texturing of Sintered Ceramic by KrF Excimer Laser

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Abstract: *Ceramics are promising materials for micromechanical components. However, due to their hardness, brittleness and contraction during sintering, surface modification is difficult using conventional techniques. In the present study the surfaces of engineering ceramic samples of an* Al_2O_3 *(34.64 wt%) SiC ceramic composites were irradiated with a KrF Excimer laser (wavelength 248 nm). The surfaces were irradiated using laser fluence in the range of 0.05 J/cm*^{2} *to 0.7 J/cm*^{2}*. The effect of laser pulse frequency (5 to 10 Hz), beam energy (300 to 750 mJ) and number of pulses (300 to 3000) upon the surface morphologies and roughness were examined. Conical structures on the treated surfaces were observed after the laser treatment. The roughness and ablation rate increase considerably with beam energy and number of pulses. The ablation depths are found to be dependent upon the type of ceramics and laser processing parameters.*

Key Words: *KrF Excimer laser; Ceramics, Surface texturing*

1.0 INTRODUCTION

An important goal of this study is to identify key needs in the Industries of the Future and to explore ways that ceramics might meet these needs. As shown in Fig. 1, the key requirements, that crosscut the Industries of the Future and that match with the favorable characteristics of ceramics, include wear resistance, corrosion resistance, temperature resistance, controlled surface behavior, dimensional stability, engineered behavior, heat recovery, and filtration. This new generation ceramics and their design methods has the potential to help the Industries of the Future reach their visions of increased efficiency, decreased maintenance, optimized recycling, increase machining capabilities and decreased pollution [1].

Conventional methods for surface texturing of ceramic materials are very difficult similar to glass machining. Traditionally, diamond-tool, abrasive jet, abrasive water jet or ultrasonic machining are used to create complex surface geometries in ceramic materials. But these processes are very time consuming and not always so precise. All laser micromachining techniques use the process of laser ablation, where the interaction of the laser energy with the sample leads to material removal. Laser ablation usually relies on the strong absorption of laser photons by the sample material, which means that the wavelength of the laser has to be chosen carefully for maximum absorption. The use of ultra fast lasers, however, has circumvented this approach since ablation takes place as a result of multi-photon absorption at high peak intensities, which means that even materials normally transparent to the laser wavelength can be machined [2].

The advantage of laser sources in industries includes fast, flexible and contact free processing. The heat input is low causing less distortion then other methods. The numerical control always used with the laser offers an easy and precision texturing. Pulsed Excimer lasers are the most commonly used lasers for fine surface texturing and precision components in the industry. The laser devices are easily configured for beam splitting and beam sharing in order to process materials at different workstation simultaneously. Excimer lasers are gas discharge lasers which produce optical output in the ultraviolet region of the spectrum. Excimer lasers are pulsed and the energy contained in a single optical pulse is measure in millijoules. Excimer lasers are typically used in machining materials which are hard to machine with other types of lasers, or where very high precision is required. The pulse length of excimer laser typically ranges from a few nanoseconds (nS) to just over 100nS [3].

Figure 1 Ceramic Material to Meet Needs of Industries of the Future.

Laser texturing of any material is a complex process involving many different parameters such as:

(i) Laser power input;
(ii) Number of pulses;
(iii) Repetition rate;
(iv) Stand off Distance;
(v) Work piece properties; and
(vi) Optophysical properties.

All these parameters need to work in tandem to produce a quality texturing operation. Excimer laser surface treatment is a newly developed method for surface modification [4]. When UV radiation is directed onto the ceramic surface the material will absorb the UV radiation strongly in the outmost layer, not exceeding a few micrometers deep, causing some components to be ablated and melted, as well as surface contaminants to be removed.

The objective of the present study is to modify the surface texture of sintered ceramics by using KrF Excimer laser micromachining. This paper discusses the interaction between KrF Excimer laser radiation and sintered ceramics. The laser energy density, pulse repetition rate and number of pulses are used as the input parameters. The effect of pertinent process parameters upon the surface morphology and its subsequent influence on surface roughness are investigated. Overall material removal mechanism in relation to the interacting parameters is discussed.

2.0 EXPERIMENTS

The set ups used for laser processing depends on several factors like laser source being used, applications etc. But the basic requirements remain the same. It consists of:

1) Laser source
2) Beam delivery system
3) Lens holder assembly system
4) Work-holding and masking arrangement

Figure 2 Experimental Set Up

1) Laser Source

The KrF Excimer Laser system used in the present investigation is a model COMPEX-201 manufactured by Lambda Physik, Germany. The specifications of the laser are given in Table 1. The laser source along with the peripheral units is used to build the micro-manufacturing center.

Table 1

Specification of the Compex 201 Laser head

Manufacturer	Lambda Physik
Type of laser	KrF Excimer Laser
Wavelength	248 nm
Pulse width	25 ns
Repetition rate	10 Hz
Maximum Pulse Energy	750 mJ
Beam Profile	Rectangular

2) Laser Peripheral Systems

The KrF Excimer laser based micro machining center comprises of the following peripheral units

- 3-axes precision work positioning stage for alignment of work piece and laser beam,
- Telescopic gas nozzle and assist gas circuit,
- Beam deflection and focusing system,
- Work-holding and masking device.

3) Work-holding and Masking Arrangement

- The work-holding device consists of two mild steel plates that can be clamped over each other with the help of fly nuts such that it can hold the ceramic work piece and mask strip.
- The masking system is required to selectively pass & block the laser beam. The system designed is such that its masking aperture can keep open only required part of ceramic,
- A manual precision vertical positioning system to alter the stand off distance setting.

4) Lens Holder Assembly System

- The laser beam coming out from the Laser head is in the horizontal direction. So to guide these laser beams vertically a beam deflector is used, which is placed at 45° with respect to the output beam so that the beam is deflected by 90° and falls perpendicularly on the work piece.
- The output beam of the laser is of rectangular cross-section 30 x 15 mm, in order to generate the necessary spot size and to deliver the required energy intensity level (fluence) as required by a particular kind of laser material processing application a focusing lens is used.
- Appropriate optics for UV (248nm) is used whose specifications are given in Table 2.

Table 2

(a) Specifications of the Reflector

Material	Fused Silica
Reflectivity	99.5 % at λ=248 nm
Dimension	50 x 20 x 5 mm

(b) Specifications of the Lens

Material	Quartz
Focal Length	300 mm
Type	Plano Convex
Diameter	50 mm
Thickness	4 mm (at middle)

3.0 MECHANISM OF MATERIAL REMOVAL

The interaction of laser with solid matter is an extremely complex phenomenon. It is not a single event, but is complex interaction of many overlapping and separate event. Some of these events include absorption, electronic excitation, rapid heating, plasma generation, photolysis, sputtering, melting, expansion, ejection, decomposition, oxidation, vaporization, sublimation, condensation, and solidification.
When laser energy is absorbed by the surface of a solid, the electromagnetic energy of the beam is converted to mechanical, thermal, chemical and electronic energy, and the resulting ablative debris, in the form of a plume, includes atoms, molecules, ions, photons, electrons, and agglomeration of fragments of the irradiated material. The mechanism of material removal can be two types:

(a) Thermal, and
(b) Cold ablation.

This is the mechanism by which material removal takes place in Excimer lasers.

3.1 Cold Processing or Cold Ablation

Some UV lasers of short wavelength, like Excimer laser, enable a transfer mechanism, which is different from thermal interaction. Photons of appropriate wavelength may cause dissociation or ionization of the irradiated material. The typical bonding and extinction energy for many molecules is in the range of 3 to 15 eV, which corresponds roughly to the range of photon energy in the ultraviolet region. UV photons, from 157 to 308 nm, provide sufficient energy for breaking bonds in a wide variety of materials. When these photons are absorbed by the martial then if the photon energy is sufficient to cause the bond breakage the bond is broken & the ablated material is removed in the vapour form [5].

4.0 RESULTS AND DISCUSSION

4.1 Spot Area Measurements

With the help of above experimental set up spot area has been obtained for different distance between lens and work piece for constant beam Energy per pulse 100mJ/Pulse. The nature of result is shown in Figure 3.

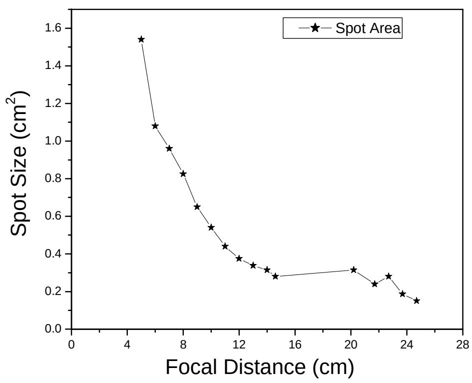


Figure 3 Focal Distance Vs Spot Size (cm^2)

It can be concluded from Figure 3 that as the focal distance increases the spot size decreases with constant beam energy, wave length and beam distribution. But the declination is not uniform because of ambience effect and beam divergence angle and some possible measurement error.

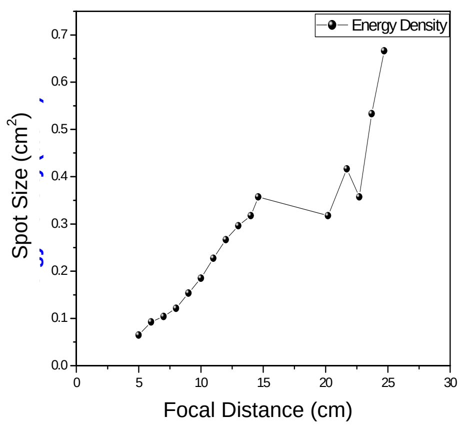


Figure 4 Focal Distance Vs Energy Density (J/cm^2)

It can be said from figure 4 that as the focal distance increases the energy density increases maximum up to focal Length of the lens, in present case up to 300 mm. Beyond this distance it will not give precise results.

4. 2 Laser Interactions with Sintered Ceramic Surface

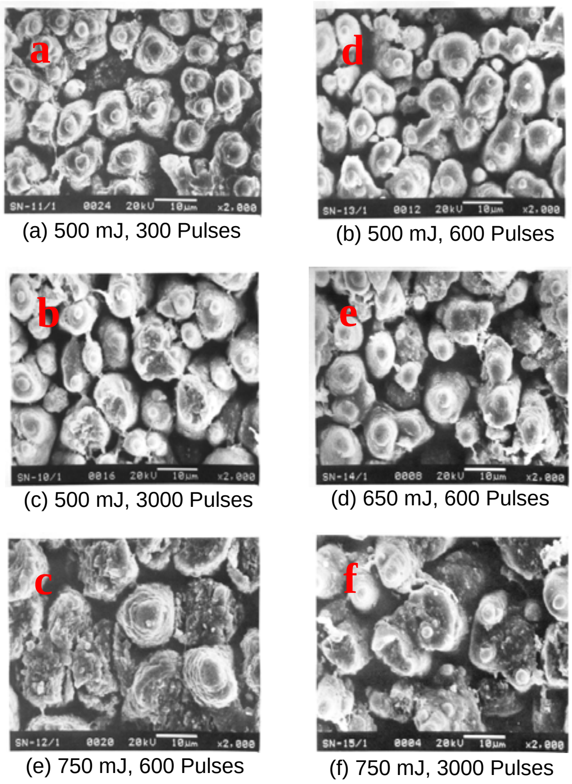
When a sintered ceramic surface is irradiated by KrF Excimer laser beam, a thin surface layer absorbs the light energy. Unlike the interactions with organic materials that cause direct bond rupture, KrF UV laser radiation normally induces thermal effects in sintered ceramic surface through vibration of electrons or co-vibration of the bonding. As the thermal conductivity of ceramic is poor and heat loss via conduction is low, the thermal energy in the thin surface can accumulate and cause melting. Dependent upon the laser energy density, the frequency of the laser pulse and the duration of the pulse, the thermal energy can further accumulate in the molten surface layer until boiling occurs and finally results in vaporization. As the rate of vaporization is high, due to the rapid high energy input and short pulse duration, an ablation effect is therefore observed.

For a particular material, there exists a threshold energy for melting and a threshold energy for vaporization. These two threshold energies are both dependent upon the melting point, boiling point, thermal conductivity, specific heat, latent heat of fusion, and latent heat of vaporization etc. If the surface consists of heterogeneous phases, impurity or imperfection regions, different melting or ablation thresholds are observed because of the different thermal properties of these phases. The roughness and morphologies of the laser-treated surfaces obtained in this work verify these points.

4.3 Surface Structures and Composition

Figure 5 show the SEM micrographs of surface areas of the laser-treated Al_2O_3+SiC composite.

The morphology mainly consists of a conical structure. The density and the height of the cones are dependent upon the incident laser energy density as well as on the sintered ceramic properties. The formation of the conical structure can be attributed to the different absorption coefficients of the constituent phases on the sintered ceramic surfaces, for example, the highly crystallized matrix phase, the amorphous particle boundaries and regions of impurities and structural imperfection. Thus, some regions absorb more energy and result in higher ablation rate than that of other regions. The difference in the ablation rate results in the formation of a peak-and-valley structure, in which the valley regions absorb more energy. As more energy is deposited onto the surface, the height difference between the valley and peak become greater and finally a conical structure is formed. The steep wall angle of the cone reduces the effectiveness of laser fluence to be irradiated on the side of the cone. Thus, once a cone structure has started to form it tends to become stable during further etching. The transition from a flat surface to peak-and-valley and finally a conical morphology is shown in Figure 5. The results also show that the amount of material ablated increases with the increase of the laser energy density. A depth of tens of microns can be produced by multiple pulses.



(a) 500 mJ, 300 Pulses (b) 500 mJ, 600 Pulses

(c) 500 mJ, 3000 Pulses (d) 650 mJ, 600 Pulses

(e) 750 mJ, 600 Pulses (f) 750 mJ, 3000 Pulses

Figure 5 SEM micrographs of Al_2O_3 Composite surface laser treated at focal distance 247 mm

The change in surface composition of the laser treated surfaces was determined by EDS (Energy Dispersive X-Ray Spectroscopy using SEM. The EDS study is shown in Table 3.

Table 3

EDS Report for Unmachined Surface:

Element	Element %	Atomic %
Al K	18.33	16.72
Si K	11.69	10.24
Cr K	5.24	2.48
Fe K	2.76*	1.22*
Ni K	13.34	5.59
Zr L	8.72	2.35
O	39.92	61.40
Total	100.0	100.0

Compound	Compound %	No. of ions
Al_2O_3	34.64	8.71
SiO_2	25.00	5.34
Cr_2O_3	7.66	1.29
Fe_2O_3	3.95*	0.63
NiO	16.97	2.91*
ZrO_2	11.78	1.23
		32.00
	100.00	
	Cation sum	20.12

EDS Report for Machined Surface:

Element	Element %	Atomic %
Al K	28.11	21.58
Si K	19.74	14.56
Zr L	3.45*	0.78*
O	48.70	63.07
Total	100.0	100.0

Compound	Compound %	No. of ions
Al_2O_3	53.11	10.95
SiO_2	42.23	7.39
ZrO_2	4.66*	0.40*
		32.00
	100.00	
	Cation sum	18.74

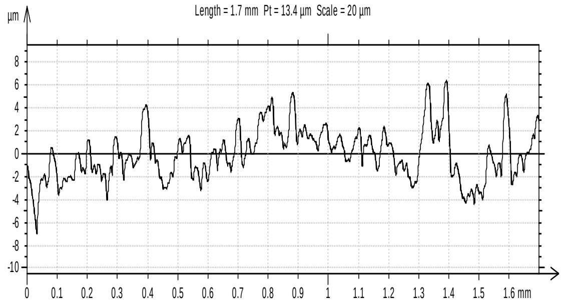
Above table 3 shows the changes in atomic concentration of the laser-treated Al_2O_3+SiC composite sintered ceramic surface with 3000 number of laser pulses at a constant laser beam energy of 750 mJ. It can be seen from the EDS report that Element % and Atomic % of Al, Si and O increases and Zr decreases with increasing number of pulses. The Compound % and Number of ions for oxides Al_2O_3 and SiO_2 increase with increase number of pulses. ZrO_2 decreases with increase number of pulses. Element % and Compound % of Al and Si with their oxides are increases with the number of pulses, this being due to the dissociation and ablation of Ni, Cr and Fe, when it is irradiated with a high energy laser beam.

5.0 EXPERIMENTS WITH TAGUCHI METHODOLOGY

Extensive trial-and-error based experimentation is done in order to obtain acceptable operating conditions for laser texturing of sintered ceramic.

5.1 Experiments for Surface Roughness Measurements

Experiments are performed by KrF Excimer laser on the Al_2O_3 composite sintered ceramic keeping stand off distance constant at 232 mm so that a spot area of 0.24 cm^2 is maintained throughout the experiments**.** The parameters and results are shown in Table 4. The mechanical surface roughness profiles were captured on a PC using Taylor Hobson Talysurf for row data collection of R_a values. A typical result of experiment 16 is shown in figure 6.



Ra=1.08µm,Rz= 7.03µm,Rmax= 7.03µm, Rq= 1.36 µm

Figure 6 A Typical Surface Roughness Profile for Experiment No16

Table 4 Experimental layout and row data

Expt No	Fluence (mJ)	No. of Pulses	Repetition Rate (Hz)	R_a (µm)
1	300	400	2	0.31
2	300	1000	5	0.53
3	300	1800	8	0.48
4	300	3000	10	0.65
5	425	400	5	0.66
6	425	1000	2	0.53
7	425	1800	10	1.26
8	425	3000	8	1.01
9	550	400	8	0.52
10	550	1000	10	0.75
11	550	1800	2	1.18
12	550	3000	5	1.39
13	650	400	10	0.83
14	650	1000	8	0.87
15	650	1800	5	1.46
16	650	3000	2	1.08

The standard analysis approach has been selected for the determination of optimum condition. “Bigger is the best” quality characteristic is selected. The optimum conditions of different parameters and desired performance details are obtain after ANOVA analysis as shown in Table 5.

Table 5

Optimum Conditions and Performance

Sl No.	Factors	Level Description	Level	Contribution
1	Fluence	650	4	0.215
2	No.of Pulses	1800	3	0.25
3	Repetition Rate	5	2	0.165
Total Contribution Fron All Factors...				0.63
Current Grant Average Of Performance...				0.844
Expected Result at Optimum Condition				**1.474**

The optimum condition 650 mJ Fluence, 1800 Number of pulses and 2 Repetition rate with Expected R_a value is 1.474 µm.
For experiment 16 with input parametrs: 650 mJ Fluence, 1800 Number of pulses and 5 Repetition rate as given in Table 4, the obtained R_a value is 1.46 µm. It shows that considering two levels among optimum required condition, a very nearby value of roughness can be obtained which appreciates the optimum condition of analysis.

6.0 CONCLUSIONS

Surface modification of Al_2O_3+SiC composite sintered ceramics using KrF Excimer laser can produce characteristic surface structures, the structures and compositions depending upon the ceramic material and the Excimer laser parameters. The Excimer laser surface treated Al_2O_3+SiC composite sintered ceramic have conical structures, which can provide the extra adhesion surface area and mechanical locking sites that is important for adhesion bonding. Significant improvement in lap-joint adhesion strength was achieved by laser treatment of the adhered surfaces.
Obtained results from optimum condition show that considering two levels among required optimum conditions, very nearby value of roughness, appreciating the optimum condition of analysis, can be achieved.

The effect of repetition rate is comparatively less then other factors so it can be kept at minimum level considering minimum operating cost.

7.0 REFERENCES

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