Chemical Assisted Laser Beam Machining of SiC Ceramic and Optimization of Process Parameters

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Abstract

Chemo mechanical laser beam assisted finishing is the process of a conceptual combination of a fundamental cognitive process. In this process, three basic concepts are synthesized to obtain a smooth surface of silicon carbide. Three different chemicals of H_2SO_4 , HCl , and HF with a 50% solution with purified water were used. Continuous mode CO_2 power from 250W-300W was used to melt the surface after acid was applied. The smooth surface was evaluated using morphology, including pore pattern, pore depth, and pore width was studied under a scanning electron microscope, and the surface roughness, wear-resistance, and hardness were analyzed using a non-contact surface profilometer, scratch tester TR-101, and Digital Rockwell hardness device respectively. The results were statistically analyzed using Design expert software analysis of variance (ANOVA). The results showed a significant change in the pore pattern, crystal structure, surface roughness, wear-resistance, and hardness. This result was verified by scanning electron microscope, optical microscope, Non-contact profilometer, and scratch tester TR-101 machine. The hardness of the smooth surface was increased as well as surface roughness and the coefficient of friction also improved as compared to substrate silicon carbide.

Introduction

Ceramic materials are interesting for MEMS aerospace applications, medical, electronic, and automotive parts. Compared to metals they have many advantages such as high temperature, wear resistance, low thermal conductivity, and low specific density. Liang et al(2018) investigated on micro-milling of silicon nitride ceramics by using a laser-assisted waterjet process, laser ablation, and liquid assisted waterjet process. They found that the laser-assisted waterjet micro-milling process was a novel technology. The laser was used to heating and soften the target material in this process. Xian Wu et al(2019) studied laser-induced oxidation of cemented carbide during micro-milling. They found that the cemented carbide surface form a porous oxide layer through the high-temperature oxidation under laser irradiation which can effectively decrease the hardness and improve the machinability of cemented carbide.

Zhao et al(2020), studied of laser-induced oxidation assisted micro-milling to machine 65 vol% SiCp/Al composites. An easy to remove the porous oxide layer which was generated when the material was treated by a nanosecond laser in an oxygen-rich environment leads to an enhancement in the machinability of the material.

Jiang et al. (1998) studied chemomechanical polishing on silicon nitride work material depends not only on the polishing conditions but also on the interactions between the abrasive work material environment. Ceramics generally have good chemical resistance to weak acids and weak bases. However, very strong acids or strong bases tend to produce ion exchange reactions and dissolve the structures. HF is commonly used to intentionally etch ceramic surfaces composed of silicates. Ramakrishnaiah et al. (2016) studied the effect of hydrofluoric acid etching duration on the surface of the ceramic. This produces different dissolution that creates micromechanical relief before micromechanical bonding. Liu and Xu(2017) studied ultra-fine polishing of glass-ceramics by disaggregated and fractionated

detonation nanodiamond(NDs). They found the number of nitro-groups on NDs surface was increased and the absolute value of ξ -potential was increased by 6 times at pH 4–5, which was advantageous to polish glass-ceramics in a mildly acidic environment.

Johnson et al. (2000) studied HF chemical etching of SiC at room temperature HF (50%) solution etches. Modification of surface by different methods improves the lifetime of parts. Surface finishing surfaces in the nanometer range, it is required to remove material in the form of atoms or molecules individually or in the groups. Advanced surface finishing processes performance and use of certain specific processes depend on workpiece material properties and functional requirements of the component. The quality of the surface is one of the significant parameters which affects the life and functionality of any product. Wang et al. (2010) studied the chemomechanical polishing for nano-scale surface finish of brittle wafers. Zhong et al. (2014) reported chemical mechanical polishing (CMP) processes for manufacturing optical silicon substrates with shortened polishing time. Wang et al. (2012) reported chemo-mechanical planarization from macro-scale to molecular-scale. To enhance the oxidation rate of SiC, directly heating the slurry through chemical reactions added an acidic or base solution in their polishing process, such as H_2SO_4 , KOH, and polished surface roughness reached 0.33 nm. The surface roughness achieved was on the order of 0.5 nm. Chemomechanical laser beam finishing (CMLB) is the new process technology in the ceramic surface finishing. Tsai et al. (2012) reported characteristics of polishing hydrophilic pad in chemical mechanical process and development more efficient of polishing pads, and provide reductions in the number of pads used, and the amounts of slurry consumed. CMLB is a cognitive process that involves a combination of chemical, mechanical, and laser beam actions. The importance of each contribution depends on the finishing work material. Jokubavicius et al. (2016) studied surface engineering of SiC via sublimation etching and modified morphology. In the process chemical reaction between the acid and the workpiece, is chemical contribution this advantage to make surface structures weak loosely bonded.

The cleaning purposes by acetone are mechanical action. Chemical and mechanical is expected to overcome many problems of surface damage associated with including pitting due to brittle fracture, dislodgement of grains, scratching due to abrasion, etc. resulting in smooth, damage-free surfaces therefore Laser beam is relocating bond structure easily by melting the surface of the workpiece and become smooth. The strong absorption of the CO_2 laser beam on the 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. Ceramic materials are candidates for use in aggressive and abrasive environments where hardness, wear resistance, and chemical inertness are essential. These mechanical properties mean that ceramics have always proved difficult to grind, polish, and etch. Przystacki et al. (2014) investigated surface roughness analysis after laser-assisted machining of $SiNO_3$ and the result indicates that laser-assisted improves machined surface roughness in comparison with conventional turning. Malshe et al. (1994) reported friction and wear properties of chemomechanical polished diamond films are measured at elevated temperatures and in the presence of various gaseous environments. The

coefficient of friction of the polished diamond films was found to be about 0.09, which is very close to that of the natural diamond (0.07).

In this work chemo-mechanical laser-assisted surface finishing difficult to machine SiC material was accomplished. There used three techniques of pre-processing workpiece material using chemicals have been investigated for better surface finish during laser beam machining of SiC block. As a result smooth surface finish was achieved at different chemicals used and its related surface hardness showed improvement. The machined surface with better surface finish showed higher wear resistance as confirmed using surface scratch testing machine. In addition the effect of laser processing parameters such as scanning speed, laser power and beam diameter on surface finish has been investigated in the work. The hardness after machining also improved due to laser beam surface radiation which homogenizing surface morphology by avoiding porosities and cracks.

Materials And Methods

In this experiment, a silicon carbide block with dimensional of 150 mm×50 mm×20 mm is prepared. The sample was cleaned using acetone from any foreign particles and made ready for work. After many literature surveys, three chemicals (hydrochloric acid, sulfuric acid, and hydrofluoric acid) are applied to the sample surface. Concentration has an equal solution of 50% acid and 50% pure water. Curing time was given 24 hours at room temperature. The method of applying acid on the sample is by brushing. The CO₂ laser beam applying on the surface of the sample. Laser parameters were selected as laser power from 250 W to 300 W and laser scan speed from 850 mm/min to 1000 mm/min at 60 mm standoff distance. Figures 1(a-c) show the experiment setup.

2.1 Experimental Design

A response surface methodology based on the central composite rotatable design (CCRD) was selected as the experimental design method. Let Ra_1 for HF acid, Ra_2 for H₂SO₄ acid, and Ra_3 for HCl acid. They are two independent variables and three response variables. The influence of the independent variable, LP (laser power) and LSS (laser scan speed) on the response variables HF (Ra), H₂SO₄ (Ra), and HCl (Ra). Table 1 shows the selected laser independent variables process parameters used in the experiment. The Design-Expert software was employed for analysis of generated data. The response (Ra) is a function of laser power and laser scan speed.

Table 1 Coded and actual levels of the input independent parameters

S.no	parameters	Units	levels				
			-1.414	-1	0	1	1.414
1	Laser power	W	240	250	275	300	310
2	Laser scan speed	Mm/min	829	870	900	950	970

Result And Discussion

The experiments were conducted and values R_{a1} , R_{a2} , and R_{a3} were measured and the values were given in Table 2. Experimental design includes 13 runs of an experiment conducted. Further analysis of variance ANOVA is performed on collected data to confirming equations 1, 2, and 3 which explains graphically R_a as a function of laser power and laser scan speed.

Table 2 Experimental design and responses for silicon carbide initial Ra (5.02 μ m) at constant standoff distance 60 mm

Std.	Laser power (W)	Laser scan speed(mm/min)	HF $R_{a1}(\mu\text{m})$	H ₂ SO ₄ $R_{a2}(\mu\text{m})$	HCl $R_{a3}(\mu\text{m})$
1	275	900	0.710	0.545	0.412
2	275	970	0.820	0.599	0.488
3	275	829	0.901	0.544	0.458
4	310	900	1.120	0.842	0.742
5	275	900	0.744	0.542	0.414
6	250	950	0.868	0.578	0.521
7	275	900	0.744	0.549	0.420
8	300	950	0.988	0.602	0.622
9	275	900	0.742	0.540	0.418
10	275	900	0.740	0.549	0.414
11	250	850	0.877	0.588	0.548
12	300	850	1.160	0.850	0.682
13	240	900	0.999	0.680	0.602

Table 3 Analysis of variance to average surface roughness quadratic models for HF (R_{a1})

Source	Sum of Squares	Degree of freedom	Mean Square	F value	p-value Prob > F
Model	0.25	5	0.05	46.07	< 0.0001
LP-Laser power	0.041	1	0.041	37.83	0.0005
LSS-Laser scan speed	0.011	1	0.011	10.03	0.0158
LP*LSS	6.64E-03	1	6.64E-03	6.1	0.0429
LP ²	0.18	1	0.18	165.69	< 0.0001
LSS ²	0.026	1	0.026	24.21	0.0017
Residual	7.62E-03	7	1.09E-03		
Lack of Fit	7.62E-03	3	2.54E-03		
Pure Error	0	4	0		
Cor Total	0.26	12			
Std. Dev.	0.033		R ²	0.9705	
Mean	0.88		Adj. R ²	0.9494	
C.V. %	3.75		Pred. R ²	0.7903	
Std. Dev.	0.054		Adeq.Pre	18.894	

3.1 Evaluation of Models

From Table 3, 4, and 5 shows the ANOVA of regression parameters of the predicted response surface quadratic model for R_{a1} , R_{a2} , and R_{a3} . Model F-value for R_{a1} of 46.07, for R_{a2} of 123.75 and R_{a3} of 62.86 low probability values (Prob>F<0.0500) indicates that the model is significant for all three cases. R^2 is more than 90%. The regression statistics of fits R^2 are the goodness of fit value for R_{a1} , (0.9705), R_{a2} (0.9888), and R_{a3} (0.9782) are close to unity. There are also indications that over 97.05%, 98.8%, and 97.82% are adequately captured. The adequacy precision of 18.894 for R_{a1} , 21.837 for R_{a2} , and 30.870 for R_{a3} respectively greater than 4 is the desired signal to noise ratios. These indicate that there are adequate signals and that these models can be used to navigate the design space. The predicted values indicated fit the data appropriately. Analysis of variance of ANOVA shows that both model terms have a significant influence on R_{a1} , R_{a2} , and R_{a3} . For the linear terms, the LP has a dominant influence on R_{a1} followed by LSS. For the square terms, LP² has a much more dominant influence on R_{a1} then LSS².

The final regression models in terms of actual factors an empirical relationship for R_{a1} , R_{a2} , and R_{a3} and the laser process variable can be expressed by second-order polynomial Eq. (1), Eq. (2), and Eq. (3)

respectively.

$$Ra1 = 31.98 - (0.1095 \times LP) - (0.036 \times LSS) - (3.26 \times 10^{-5} \times LP \times LSS) \\ + (2.58 \times 10^{-5} \times LP^2) + (2.46 \times 10^{-5} \times LSS^2) \dots \dots \dots (1)$$

$$Ra2 = 22.06 - (0.097 \times LP) - (0.018 \times LSS) - (4.76 \times 10^{-5} \times LP \times LSS) \\ + (2.59 \times 10^{-4} \times LP^2) + (1.698 \times 10^{-5} \times LSS^2) \dots \dots \dots (2)$$

$$Ra3 = 44.6 - (0.158 \times LP) - (0.05 \times LSS) - (6.6 \times 10^{-6} \times LP \times LSS) \\ + (3.03 \times 10^{-4} \times LP^2) + (2.87 \times 10^{-5} \times LSS^2) \dots \dots \dots (3)$$

Based on the model, the most sensitive parameter affecting surface roughness value was laser power. Figure 2 shows a typical graph of the HF sample. Average surface roughness values first decreased from 240W the linear increased from 275 W-300W, the highly increased after 300W to 400W for all scan speed from 830 mm/min to 1200mm/min. The best surface roughness value was obtained at 275W. The highest scan speed 1200 mm/min has the worst roughness values. The scan speed between 900-950 mm/min has the lowest surface roughness values of 0.736 μ m.

Tables 4 shows the ANOVA of the regression parameters of the predicted response surface quadratic model for Ra_2 . Analysis of variance of ANOVA shows that both model terms have a significant influence on Ra_2 . For the linear terms, the LP has a dominant influence on Ra_2 followed by LSS. For the square terms, LP^2 has a much more dominant influence on Ra_2 then LSS^2 . The final regression models in terms of actual factors an empirical relationship for Ra_2 and the laser process variable can be expressed by second-order polynomial Eq. (2). The effect of laser power for the H_2SO_4 sample was shown in Figure 3. The same trend of graph profile was observed as HF samples. Except for that lowest Ra values of 0.545 μ m obtained at 275 W and 900 mm/min scan speed. The maximum scan speed for this sample has also the highest Ra values.

Table 4 Analysis of variance of average surface roughness quadratic models for (Ra_2)

Source	Sum of Squares	Degree of freedom	Mean Square	F value	p-value Prob > F
Model	0.25	5	0.049	62.86	< 0.0001
LP-Laser power	0.033	1	0.033	42.28	0.0003
LSS-Laser scan speed	0.013	1	0.013	16.49	0.0048
LP*LSS	0.014	1	0.014	18.05	0.0038
LP ²	0.18	1	0.18	233.37	< 0.0001
LSS ²	0.013	1	0.013	15.99	0.0052
Residual	5.49E-03	7	7.84E-04		
Lack of Fit	5.48E-03	3	1.83E-03	570.6	< 0.0001
Pure Error	1.28E-05	4	3.20E-06		
Cor Total	0.25	12	R ²	0.9782	
Std. Dev.	0.028		Adj. R ²	0.9627	
Mean	0.57		Pred. R ²	0.8453	
C.V. %	4.92		Adeq.Pre	21.837	

Tables 5 shows the ANOVA of the regression parameters of the predicted response surface quadratic model for R_{a3} . Analysis of variance of ANOVA shows that both model terms have a significant influence on R_{a3} except product term. For the linear terms, the LP has a dominant influence on Ra2 followed by LSS. For the square terms, LP² has a much more dominant influence on Ra2 then LSS². The final regression models in terms of actual factors an empirical relationship for R_{a3} and the laser process variable can be expressed by second-order polynomial Eq. (3). Figure 5 shows the surface roughness as a function of laser powers for different scan speeds. The trend of the graph shows three different profiles first linear decrease from 240 W powers to 275 W powers. The slow increased between 275 W to 350W, after which high rose. The optimized value is between 250 W and 275W powers, the roughness values of these powers are, 0.521µm and 0.415µm, respectively. For the HCl sample, laser power has significantly influencing parameters on roughness values.

Table 5 Analysis of variance to average surface roughness quadratic models for R_{a3} .

Source	Sum of Squares	Degree of freedom	Mean Square	F value	p-value Prob > F
Model	0.29	5	0.058	123.75	< 0.0001
LP-Laser power	0.023	1	0.023	49.65	0.0002
LSS-Laser scan speed	2.731E-003	1	2.731E-003	5.79	0.0471
LP*LSS	2.723E-004	1	2.723E-004	0.58	0.4724
LP ²	0.25	1	0.25	529.51	< 0.0001
LSS ²	0.036	1	0.036	75.98	< 0.0001
Residual	3.304E-003	7	4.720E-004		
Lack of Fit	3.299E-003	3	1.100E-003	845.88	< 0.0001
Pure Error	5.200E-006	4	1.300E-006		
Cor Total	0.30	12		R ²	0.9888
Std. Dev.	0.022	—		Adj. R ²	0.9808
Mean	0.47	—		Pred. R ²	0.9205
C.V. %	4.59	—		Adeq.Pre	30.870

3.2 Surface Roughness and Morphology

The roughness value before and after chemomechanical laser surface finishing is given in the percentage of more roughness presented on the surface as given in Figure 5. The rough surface of the original SiC has 76% while after the application of chemo-mechanical laser-assisted finishing the presence of rough surface or peaks are highly reduced in the order 6%, 7%, and 11%, for three acids HCl, H₂SO₄, and HF respectively. HCl is a strong acid that caused more weakening of the strong ceramic bonding before the laser beam was applied. The measured average Ra value is 0.355. The second improved surface was by application of sulfuric acid for which after laser beam application average Ra value of 0.475 µm was obtained. Among the three acids used the least, an improved Ra value of 0.744 µm was achieved by the application of HF acid. The original SiC material average Ra was 5.02 µm. The 3D and 2D profilometer images of Figure 6 confirmed that the smooth surface obtained after laser melting.

The morphology after laser finishing as shown in Figure 7 for HCl material. The interface region of laser melted region 'I' and recast layer region 'II' were seen in Figure 7(a). The breakdown of smaller round grains has a minimum diameter of 11.6µm (Fig. 7b). After the grains joined their maximum lateral width after joined tighter have about 50.27µm. Every surface atom is closely packed. The morphology shows remelted grains have a circular shape as the arrow head is shown in Figure 7(d).

From the morphology of optical and FESEM images, melting and solidification of thin layers filled the valleys and as a result, the roughness of the sample improved. Higher magnifications up to 1.5 K give a good image of surface atoms. A small ball-like structure was also seen as the arrow shown in Figure 7 (d).

Figure 8 shows optical images of H_2SO_4 samples 3D and 2D images. A smooth surface was seen on the topology. The melted surface filled the roughness areas and smoothening the part. Further study of the morphology was conducted using optical microscopy and FESEM analysis given in Figures 9(a-d). The quality of surface finish was confirmed how the surface atoms melted and joined together to form a smooth surface were studied by optical images of Figure 9(a) and 9(b). Three separated regions were visible as substrate region 'I' as the top layer, recast layer of region 'II' at the middle, and laser melted region 'III' at the bottom layer. The recast layer thickness of 200 μm was formed. The laser melted region was shown in Figure 9(b). The surface grains look complete roundness with a minimum diameter of 14.13 μm and after they joined the lateral dimension was measured as 158 μm . When compared with the HCl sample surface grain dimensions are higher which is due to more roughness of the H_2SO_4 sample than the HCl sample. The melted surface morphology was also studied using FESEM has shown in Figure 9(c) and 9(d). The arrowhead in Figure 9(d) shows rounded surface grains which were also seen in optical images. A good melt morphology with surface grains was remelted together forming good surface bonding. There are no metallurgical defects observed in the morphology as investigated using higher-resolution electron images of FESEM. The main factor for the improved surface was due to H_2SO_4 acid has etched the surface of SiC ceramic which later make a laser beam to melt easily and re-bonding structure formation.

Surface finishing of the HF sample was investigated from 3D and 2D profilometer image (Fig.10) The surface topology has two portions of the laser finished part and the original surface. The average surface roughness value was improved by 90% after chemomechanical laser-assisted finishing was conducted. Optical images are shown in Figure 11(a) recast layer were seen and Figure 11(b) micro-crack was observed. The morphology at the higher resolution of FESEM after laser melting was shown in Figure 11(c) and 8(d). The surface roughness of the HF sample is less improved than HC and H_2SO_4 samples which are due to the formation of microcracks and impurity segregation in the morphology of the melt region. The black portion showed in Figure 11 (a) of the circle mark shows un-melt core silicon atoms in the recast layer.

The formation of microcrack was seen in the melt region as the arrowhead shown in Figure 11(b) unmelted core segregation was seen in the morphology as shown in Figure 11(c). Un melted impurity shown in the circle mark may cause cracks to be formed.

The effect of applying HF acid may cause more damage to the workpiece. After the laser beam was applied the surface atoms suffered in forming microcracks. The defect in the material which will reduce its important surface performance to protect wear and corrosion. Care should be taken while applying HF acid for chemo-mechanical laser surface finishing application.

3.3 Study of surface hardness

The hardness of any material plays a great role in imparting good wear and corrosion performance of ceramic materials. The effect of laser melting on the hardness of SiC material was investigated during chemo-mechanical laser-assisted surface finishing. For three chemicals used the hardness after laser melting was compared with SiC as received hardness. Figure 12 shows the graph of hardness Vs chemicals used in this work. The average hardness of the original SiC material is 41.05 HRA. After chemomechanical laser-assisted finishing, the average maximum hardness of 55.27 HRA was achieved for the HF sample. For the other two samples the hardness is very near as 51.47 HRA and 49.75 HRA for the H_2SO_4 sample and HCl sample, respectively. The hardness of the three samples shows more than the original SiC material.

3.4 Study of the coefficient of friction

The study of abrasion wear surface was conducted on a scratch testing machine for five loads from 20N-60N. The coefficient of friction values of the three samples was compared with SiC substrate material. Figure 13 shows the average coefficient of friction as a function of scratch loads for three samples and substrate material. The coefficient of friction values is reduced after a chemical used for laser assisting. From Figure 10, the minimum values of the average coefficient of friction were achieved for the HF sample, at minimum load from 20N, 30N, and 40N, the values are 0.537, 0.435, and 0.432 respectively. When the load is increased to 50 N and 60N, the values of the friction coefficient are 0.41 and 0.40. It is observed from hardness is the highest of other samples. Samples processed with the H_2SO_4 sample, where its average friction coefficient is 0.0.574, 0.539, and 0.471 for 20N-40N loads. For this sample, higher loads have minimum values as 0.468 and 0.448, for 50N and 60N loads, respectively. It is observed that HCl material has 0.625, 0.598, and 0.496 for 20N-40N load and minimum of 0.461 and 0.458 when the load reached to 50 N and 60N, respectively. From this work, the investigation on original SiC material has the least hardness but the highest coefficient of friction values. The minimum loads from 20N-40N have, 1.16, 0.97, and 0.90, respectively, while 50N and 60N, loads calculated values of friction coefficient are 0.86 and 0.80, respectively. The effect of the normal load was investigated for all samples that increasing the scratch load, the coefficient of friction values decreases linearly.

From wear scar profilometer is not visible to measure the depth and width of scratch due to the black surface nature of Sic material, abrasion wear values were not quantified in this work. This will be solved in our next work. In general, from the trend of hardness improved and coefficient of friction values, we expect abrasion wear resistance of HF, H_2SO_4 and HCl, were ranked in their order of decreasing abrasion wear resistance.

Conclusion

In this work chemo-mechanical laser-assisted surface finishing difficult to machine Sic material was accomplished. The main finding of this work is summarized as follows;

- Using chemical of less dilution minimum of 50 % with purified water and applying on the ceramic surface for at least 24hour before laser melting, reduces the bond structure of surface atoms which assists, during laser melting, even less power will easily machine ceramics.
- The average surface roughness values were improved from micro range to nano ranges
- The hardness of remelted layers with the help of chemicals will not affect hardness values, even the hardness increased to some extent.
- The coefficient of the highly smoothed surface is less than the original material of SiC.
- Increasing normal load has a significant role in friction values.

Declarations

Ethical Approval: The manuscript has not been submitted to more than one journal for simultaneous consideration. The submitted work is original and has not been published elsewhere in any form or language. The corresponding author confirms that all of the other authors have read and approved the manuscript and no ethical issues involved.

Consent to Participate: All experimental work and written material in this research has been done by all authors only. So there is no need of taking consent from others.

Consent to Publish: On behalf of all other authors, corresponding author understand that the text and any pictures or videos published in the article will be used only in educational publications intended for professionals. If the publication or product is published on an open access basis, I understand that it will be freely available on the internet and may be seen by the general public.

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Availability of data and materials: All authors are making assure that all data and materials as well as software application or custom code support their published claims and comply with field standards.

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Figures

Figure 1

Photograph of experiment set up (a) Chemicals, (b) laser setup and (d) samples after laser finishing

Figure 2

Effect of laser power and laser scan speed on Ra1 for HF acid.

Figure 3

Effect of laser power and laser scan speed on Ra2 for sulfuric acid.

Figure 4

Effect of laser power and laser scan speed on Ra3 for HCl

Figure 5
Pie -chart of roughness on the surface for different chemical

Figure 6
The 3D and 2D profilometer image of HCl finished sample

Figure 7

Optical and FESEM images of HCl sample; (a) interface region (X10), (b) melted region (X10), (c) FESEM image at low magnification (X250) and higher magnification of (X1.5k)

Figure 8

3D and 2D profilometer image of H2SO4 sample

Figure 9

Optical and FESEM images of H2SO4 sample; (a) interface region (X10), (b) melted region (X10), (c) FESEM image at low magnification (X500) and higher magnification of (X5k)

Figure 10

3D and 2D profilometer image of HF sample

Figure 11

Optical and FESEM images of HF sample; (a) interface region (X10), (b) melted region (X10), (c) FESEM image at low magnification (X1.5k) and higher magnification of (X2k).

Figure 12

Hardness of different samples after and before laser finishing

Figure 13

Coefficient of friction values as a function of scratch loads