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Characterization of hybrid laser-electrochemically machined cavities by areal surface roughness parameters

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Abstract
Hybrid laser-electrochemical micromachining process involves the simultaneous application of electrochemical machining and laser source in the same machining zone. With this process, a hierarchical cavity structure is observed where the central region is dominantly exposed to laser-ECM interaction and the region towards the edge is mainly exposed to the electrochemical machining process. Thus, a surface roughness gradient exists within the cavity due to application of process energies of different nature at different scales. This work presents a methodology and the results of areal surface roughness measurements (S_a, S_z, S_q and S_{dq}) in different zones of the cavity. The cavity point-cloud is measured using a Sensofar® Neox microscope in continuous confocal mode. To get the information of surface quality in different zones of the cavity, Matlab® code was written for dedicated filtering and extraction of regions of interest. The extraction and filtering methods are discussed. The correlation of the roughness parameters with the process parameters such as the laser pulse energy and the machining voltage is studied.

Keywords: Hybrid machining, laser-ECM, electrochemical machining, areal surface roughness, surface metrology.

1. Introduction and process scheme

Hybrid machining refers to simultaneous or concurrent application of two or more processes in same machining zone or within same machine [1]. This helps to push the boundaries of exisitng process capabilities and broaden the exisitng material processing window. Hybrid laser-electrochemical micromachining process involves simultaneous application of two time-dependent process energy sources (i.e. ECM and laser) in the same machining zone [2]. This is accomplished by using a hybrid tooling concept where the tool acts both as an ECM tool with sufficient cross-sectional conductive area as well as multimode waveguide for the laser. Figure 1 shows a process schematic of the hybrid laser-ECM process with major peripherals. The electrolyte enters radially into the machining head and the laser is focussed close to the entrance of electrolyte in the tool where it propagates further by means of multiple reflections (diffuse and specular) from the internal surface of the metallic tool. Process details have been discussed in details in reference [3].

Figure 2 shows examples of cavities machined by ECM and hybrid laser-ECM process with a tubular hybrid-tool of external diameter 1.2 mm and innermost diameter of 0.35 mm. With this hybrid process, a hierarchical cavity structure is observed where the cavity centre is dominantly exposed to laser-ECM interaction whereas the peripheral region is exposed mainly to the electrochemical process. Thus, a surface roughness gradient can be expected within the machined cavity due to application of different process-energies at different scales or due to existence of different removal mechanisms in different regions of the cavity. Besides this, the cavity surface has varying slope, curvature and aspect-ratio in different regions. For such complicated surfaces, it is difficult to measure surface roughness in different zones using state of the art commercial software. Therefore, the current work deals with characterization of areal surface roughness in different zones of the cavity. The point cloud data is acquired using a Sensofar Neox® microscope in continuous confocal mode and the extraction of zones, filtering and measurement is carried out using an in-house written Matlab® code following ISO-25178-2:2012. The characterization and analysis procedure is discussed. Subsequently, quantative surface roughness data in different zones of the cavity is presented and correlated with process parameters.

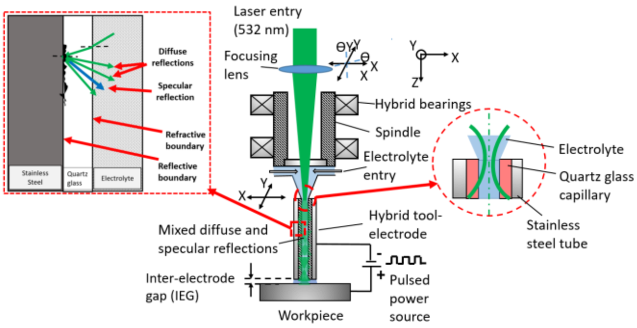

Figure 1. Process schematic of hybrid laser-electrochemical micromachining process.

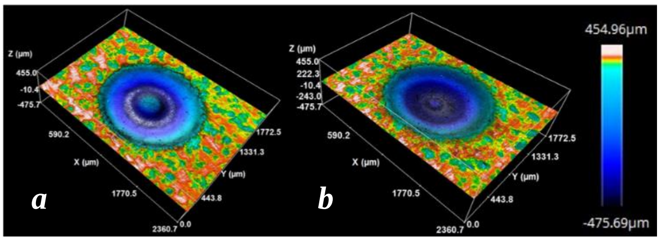

Figure 2. Exemplar cavities (1.8 mm x 2.5 mm, Sensofar Lynx®) fabricated by (a) electrochemical micromachining (b) hybrid laser-electrochemical micromachining.

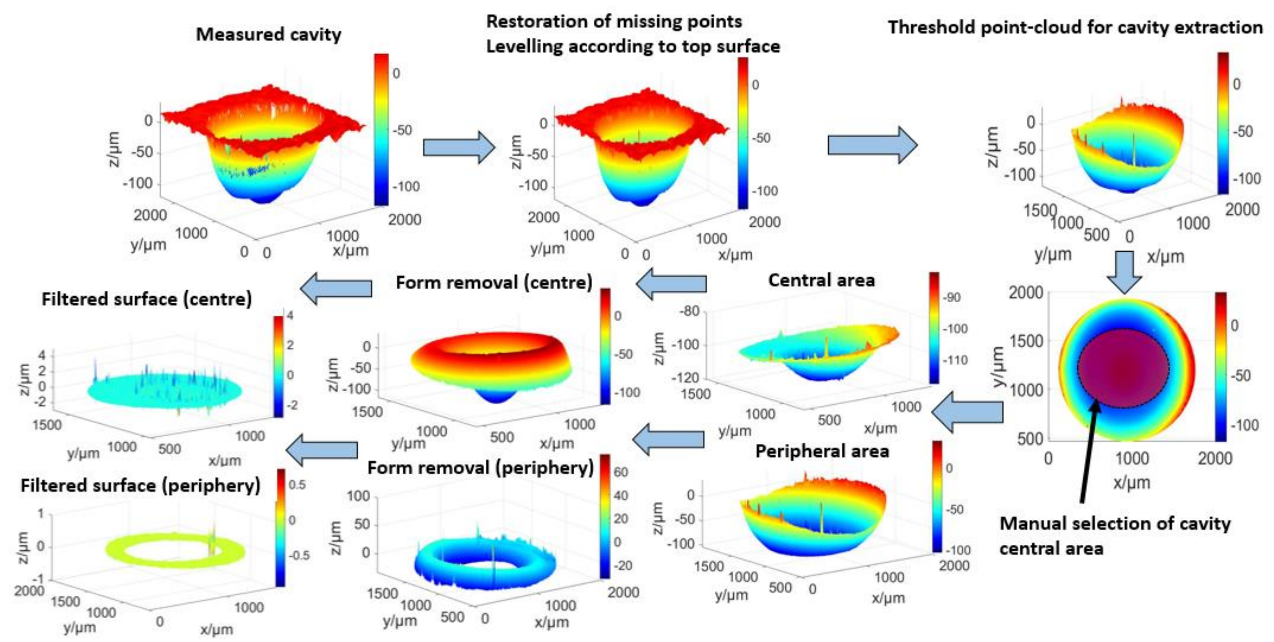

Figure 3. Schematic illustration of procedure used in Matlab® for characterization of areal surface roughness in different zones of cavity.

2. Methodology and analysis

An in-house developed hybrid laser-ECM machine tool was used for machining. The major peripherals of the hybrid machine-tool include a granite gantry-type motion platform, a 532 nm ns pulsed laser source, a micro-second pulsed voltage source, electrolyte handling system, hybrid machining head and a LabVIEW® based man-machine interface. Cavity machining experiments were carried out at different values of laser pulse energy and voltage. Other parameters were maintained constant such as the initial interelectrode gap of 20 µm, spindle RPM 400, ECM pulse on time and duty cycle 10 µs and 50 %, laser pulse on time 50 ns and electrolyte 200 *g/l aq.* $NaNO_3$. Three cavities were machined for each set of parameters. The machined samples were then subjected to cleaning in an ultrasonic bath for 20 minutes to remove the salt particles and reaction products remaining on workpiece surface after machining. The point cloud data of the cavity surface was acquired using a Sensofar Neox® microscope in continuous confocal mode which offers a high scanning speed without compromising on the quality of measured data. The complete cavity was scanned using automated image stitching. The measurement settings are depicted in Table 1. It is difficult with the commercial software to characterize the surface roughness in different zones of the cavity. Therefore, a Matlab® code was written in-house to process the topography data. The roughness measurement procedure is illustrated briefly in Figure 3. The measured point cloud data is imported in Matlab® after being subjected to missing point restoration (in the Sensofar® software) and then subjected to levelling in Matlab® based on the top surface. Subsequently, the cavity of interest was extracted from the acquired point cloud data. In ECM and hybrid laser-ECM, the cavity topography changes with process parameters which implies that in some cavities a residual pin exists in the centre and in other cavities there is accelerated dissolution in the centre. Therefore, it was difficult to automate the code for the detection of the central zone. Consequently, a manual selection of cavity central region is incorporated in the code by creating an elliptical selection tool. Following the manual selection of the central region, the point cloud data are dealt separately for the central region and the peripheral region to evaluate areal surface parameters in different zones of the cavity. The form was removed from the cavity central region and peripheral region by fitting a polynomial of degree 5. A 5 pixel median filter was employed for the peripheral region of the cavity to remove the peaks of centre that were left over from the with peripheral surface due to the manual selection. Subsequently, the roughness topography was extracted from the point cloud data by using an areal Gaussian regression filter (ISO 16610-61) and cut off wavelengths 2.5 µm (*S-filter*) and 25 µm (*L-filter*).

Table 1 Measurement settings

Parameter	Value
Objective magnification	20x
Numerical aperture	0.45
L-filter nesting index	25 µm
S-filter nesting index	2.5 µm

The areal parameters used in current investigations are: S_a (arithmetical mean height of a surface), S_q (root mean square height of a surface), S_z (maximum height of a surface) and S_{dq} (root mean square gradient/slope of the surface). These parameters were evaluated in the code using the definitions and procedure as given in ISO 25178-2:2012.

3. Results and discussion

Figure 4 shows the variation of areal surface parameters in the central and peripheral regime of the cavity at different values of laser pulse energy. An example of a roughness profile of the central and peripheral region is shown in Fig. 5. The ECM voltage is taken constant as 20 V. It is evident that typical roughness parameters (S_a, S_q, S_z, S_{dq}) are strongly dependent on the laser pulse energy for both the central and peripheral regions. It can be observed from Fig. 4 (a) that the S_a value in the centre of cavity is the highest for the ECM process (without laser) and then it starts decreasing upto 30 µJ and thereafter rises again at laser pulse energies of 45 and 60 µJ. This can be explained on the basis of observations that in ECM process (without laser), there exists a central undissolved pin-like structure which is rough and a characteristic feature of a low current density region. This makes the S_a value in the centre higher. In case of pulse energies of 10, and 30 μJ; the laser induced rise in current densities lead to reduction of the pin-height and lead to relatively better surface quality. Thus, S_a values are lower in the centre. For pulse energies of 45 and 60 μJ, the heat input in the machining zone increases and a transition of material removal mechanisms takes place from laser assisted electrochemical dissolution due to a combination of thermal and electrochemical mechanisms. Thus the S_a value starts to rise again. The peripheral region is a high current density area directly below the conductive area of the tool. The peripheral region is outside the direct interaction of laser-ECM zone, therefore there is no significant change in S_a values in this region with an increase in laser pulse energy.

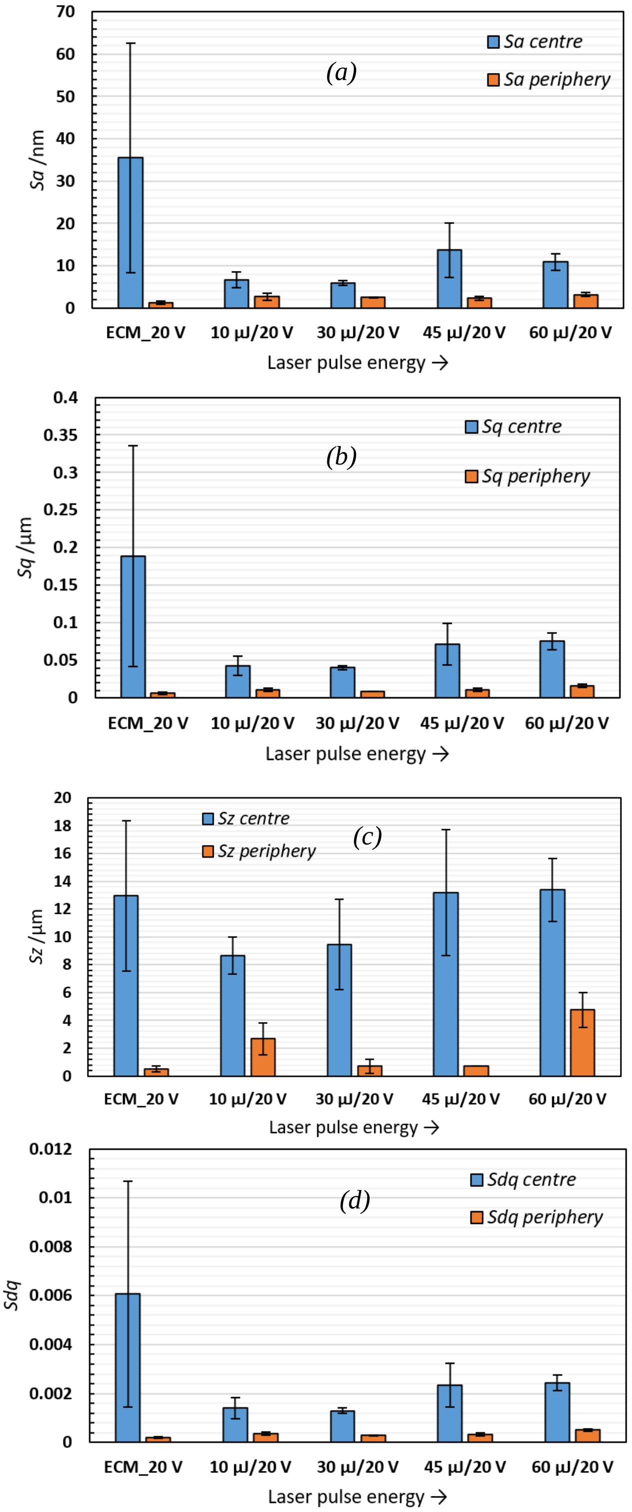

Figure 4. Variation of areal surface roughness parameters with laser pulse energy (a) S_a (b) S_q (c) S_z (d) S_{dq}.

Although the average S_a values in the peripheral region are marginally higher for laser-ECM as compared to the ECM process. The representative S_a values in peripheral region are below 5 nm for all the values of the laser pulse energy.

The S_a parameter represents an optimistic ECM/laser-ECM surface as it averages out the peaks and valleys height over the 3D surface. Figure 4(b) represents the variation of S_q with laser pulse energy in laser-ECM process. S_q represents the root mean square value of the ordinates. It can be observed that inspite of considerable difference in the obtained S_a and S_q values, the assessment of surface quality follows similar trend as that of S_a for both central and peripheral region. In order to characterize the sum of the largest peak height value and the largest valley depth value on the surface of interest, the S_z parameter was used. The measured S_z values are plotted in Fig. 4(c) for both the central and peripheral area. It can be observed that S_z values in the centre are several times higher as compared to those of peripheral region. The reason for the high S_z value in the central region can be attributed to the complex nature of the surface itself. In some of the cavities, there is a residual undissolved pin while in other cavities there is a depression in the centre. The material removal mechanisms are also changing with parameters from purely electrochemical to laser assisted electrochemical to some degree of thermal removal mechanisms. Furthermore, it is difficult to filter out the complete form in the central region even with higher degree polynomials. Figure 4(d) depicts S_{dq} values of the central and peripheral region. The S_{dq} parameters represent the root mean square of slopes at all points in the area of interest. It takes into account both the surface amplitude and spacing. It is evident from Fig. 4(d) that the central region has much a higher slope than the peripheral region. The S_{dq} value is highest for ECMed surface due to the presence of the undissolved pin-like-structure which contributes to the high slope. Also, it can be explained on the basis of S_z values that the ECMed central area has higher peaks and valley heights which contribute to higher slope change and hence higher S_{dq} values. With the laser-ECM process, the average S_{dq} value starts to decrease up to a pulse energy of 30 μJ and then increases again at laser pulse energies of 45 and 60 μJ. This is because at pulse energies of 10, 30 μJ; the laser assisted electrochemical dissolution lead to reduction in undissolved pin-height and better surface quality. Therefore the slope change is lower compared to solely ECM process. Consequently, the S_{dq} values are lower. For pulse energies of 45

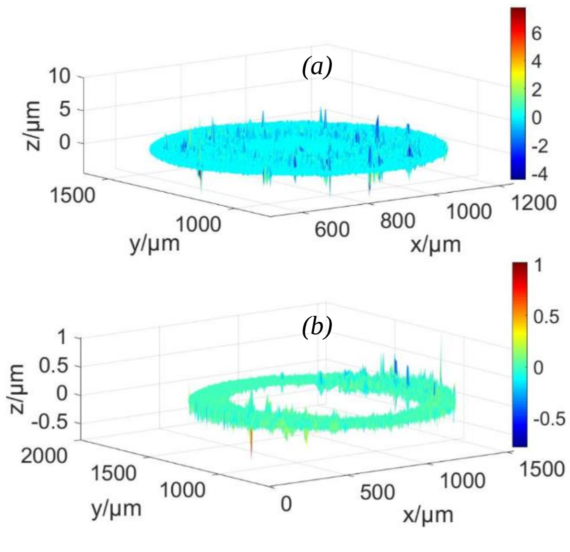

Figure 5. Example of a roughness profile of (a) central region (b) peripheral region for Laser-ECM process with parameters 45μJ/20V.

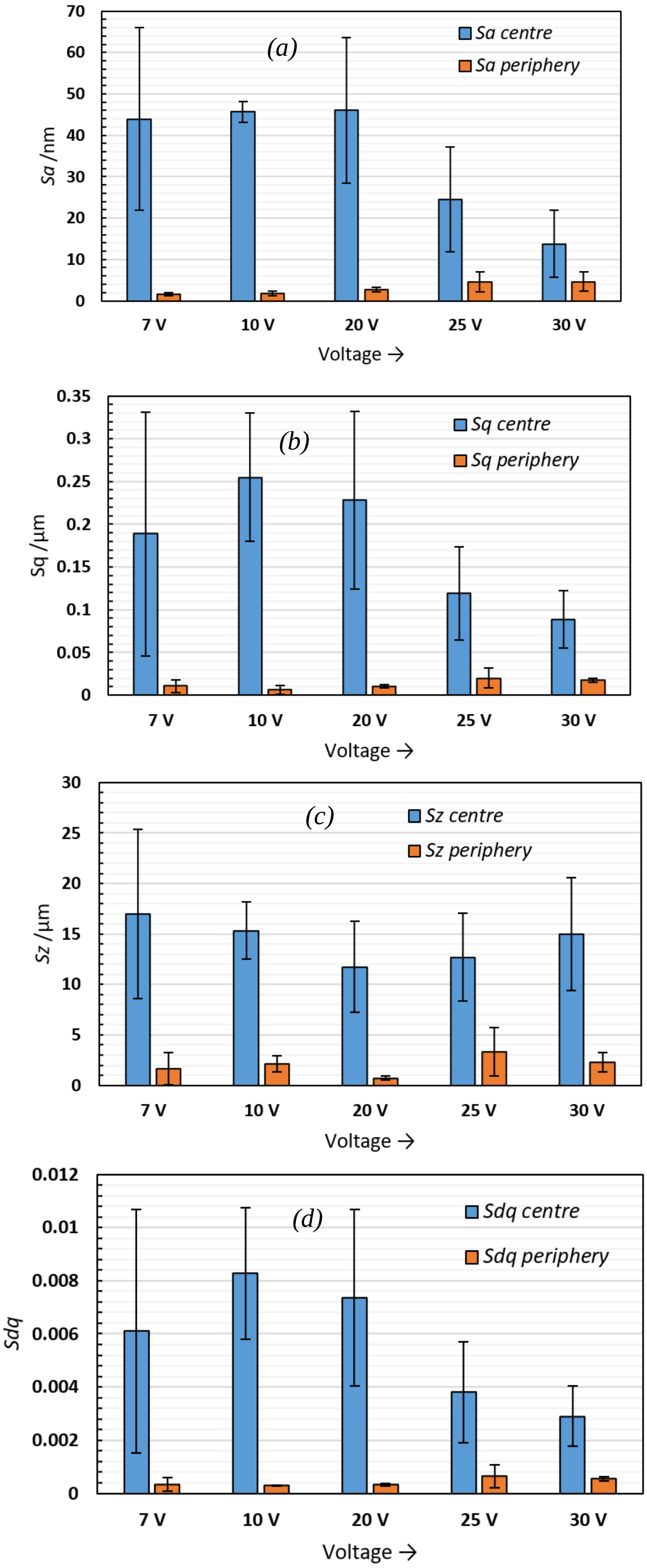

Figure 6. Variation of areal surface roughness parameters with ECM voltage (a) S_a (b) S_q (c) S_z (d) S_{dq}.

and 60 μJ, the process exhibits signs of thermal removal mechanisms on some workpieces and hence S_{dq} starts to rise again. There is no significant change (only a marginal change) of S_{dq} values of the peripheral region with a change in parameters.

In the laser-ECM process, there are two different process energies (i.e. ECM and laser) acting in the same machining zone. The energy input of the laser is characterized mainly by the laser pulse energy which is already discussed. For the ECM process, the process energy input is characterized by the current density which is related to the process voltage for fixed gap impedance. The areal roughness parameters at different process voltage without applying the laser are depicted in Fig. 6. With a tubular tool, the central part of cavity experiences low current density as compared to the peripheral region which is directly below the conductive area of the tool. Thus, S_a values of the central part are several times higher than the peripheral region. The average S_a values in the central region are nearly similar for 7, 10 and 20 V and start to decrease from 25 V. This is because at 25 and 30 V, the current densities are higher and the machining proceeds towards central region leading to dissolution of residual pin-like structures. For the peripheral region, the average S_a values are below 4 nm for 7, 10 and 20 V and increase mariginally at 25 and 30 V. The S_q, S_z and S_{dq} measurements show a similar trend as S_a and can be explained on the basis of similar reasons.

4. Conclusions

The following points can be concluded from the above research:

1. The surface roughness differs siginificantly between the central and peripheral region of the cavity. This is due to the different removal mechanisms present in the central and peripheral region. In the laser-ECM process, the laser-ECM interaction is prevalent in the central region as compared to the peripheral region. Furthermore, within the central region of the cavity, the surface roughness changes with the laser pulse energy. This can be attributed to the changing material removal mechanisms from electrochemical dissolution to laser assisted electrochemical dissolution to combined laser and electrochemical removal.
2. The effect in point 1 has been characterized by areal roughness parameters. These parameters depict a similar trend but at a different magnitude. In case of pulse energies of 10, 30 µJ; the laser assisted electrochemical dissolution lead to relatively better surface quality. Thus, S_a, S_q values are lower in the centre as compared to ECM. For pulse energies of 45 and 60 µJ, the heat input in the machining zone increases and a transition of material removal mechanisms takes place from laser assisted electrochemical dissolution to combination of thermal and electrochemical mechanisms. Thus S_a, S_q value starts to rise again.
3. When only ECM process is used, the central region experience low current density and shows high surface roughness as compared to the peripheral surface which shows a smooth/shiny surface as it is directly below the conductive area of the tool. With an increasing voltage, the central undissolved pin-like-structure starts to dissolve and the surface roughness improves. This effect corresponds to the measured *Sa*, *Sq* and *Sz* parameters. Reduction in the *Sdq* parameter at 25 and 30 V also indicates slope reduction due to dissolution of central residual pin and improvement of the surface quality in the central region.

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