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Research on hybrid laser-electrochemical micromachining : Prototype machine-tool development and test-machining results

Krishna Kumar Saxena, Jun Qian, Dominiek Reynaerts

Micro-& Precision Engineering Group, Department of Mechanical Engineering, KU Leuven, Belgium.
Member Flandersmake, Leuven, Belgium.
dominiek.reynaerts@kuleuven.be

Abstract

The trend in product miniaturization alongwith the advent of novel materials such as those with conductivity variations, superalloys with thermal barrier coateings, multilayered materials, additively manufactured materials, etc. have created a major challenge for the machining industry. It requires to extend the boundaries of existing machining processes by developing innovative hybrid machining processes. This paper presents a novel hybrid laser-electrochemical micromachining technology. The development of a protoype machine-tool for this hybrid laser-ECM process is presented. To verify the effectiveness of the hybrid laser-electrochemical process, machining experiments have been performed on Inconel 718 superalloy. The point removals have been analyzed and a comparative study of ECM and laser-ECM is presented. It shows that laser-assisted electrochemical machining achieves higher current densities, accelerated material removal rates and improved surface finish in localized regions.

Hybrid micromachining, Laser-electrochemical micromachining, hybrid machine-tool

1. Introduction and description of process

The idea behind hybrid micromachining is to combine different machining processes/mechanisms to manufacture components with a better machining performance, eventually obtaining the "1+1=3" effect [1]. The trend of developing hybrid processes is due to the advent of novel materials with extreme properties, metallurgical constraints, and improved surface integrity which were previously difficult or impossible to machine with existing conventional and nonconventional machining technologies [2]. One of the promising hybrid micromaching technologies is the hybrid laser-electrochemical micromachining process, which combines laser and electrochemical process energy in same machining zone [3][4]. Some initial research on jet-ECM based hybrid laser-ECM process has been reported in [5], however jets cannot be used for machining features of high aspect ratios and exhibit limited shape precision owing to hydraulic jump at the machined surface.

In this work, a novel configuration of a hybrid laser-electrochemical micromachining process is presented. This process combines two process energies i.e. microsecond pulsed ECM and nanosecond pulsed green laser along the same machining axis. The use of a special tube electrode for both beam guiding and electrolyte supply enables coaxial application of two process energies at higher machining depths. Figure 1(a) and (b) show experiments of hybrid laser-electrochemical process where both laser and electrochemical process energies are along same machining axis. Figure 1(c) depicts an image from a CCD camera illustrating the relative laser intensity distribution inside the electrolyte after exiting from tube electrode. The assistance of laser as a localized heat source to electrochemical machining shows positive benefits in terms of increasing current densities during machining and thereby accelerating material removal rates.

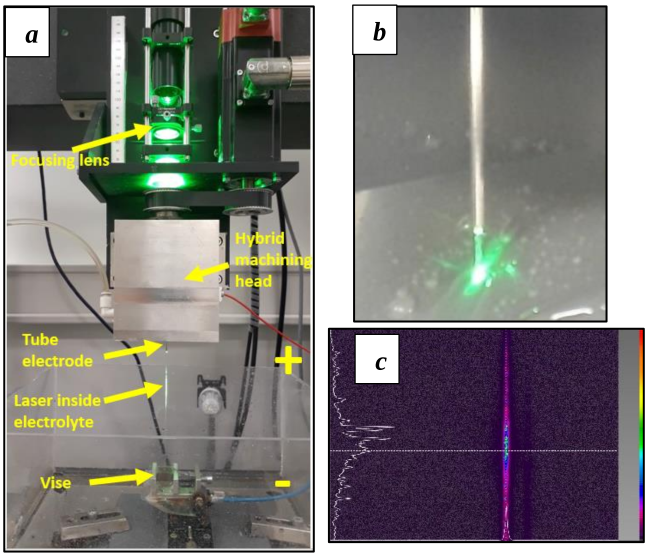

Figure 1. (*a&b*) Experiments of hybrid laser-ECM process where both laser and ECM act on same machining axis. (*c*) Relative intensity distribution of laser inside electrolyte after exiting from tube electrode.

2. Prototype hybrid machine-tool development

To combine laser and electrochemical micromachining on same machining axis and perform experimental investigations, a prototype hybrid machine tool has been recently developed at KU Leuven. The prototype machine tool is infact a multifunctional equipment, being capable of both micro-ECM and hybrid laser-ECM micromachining. Figure 2 shows the CAD model and the actual picture of the developed machine-tool. The equipment consists of a granite gantry-type machine frame, motion stages, a laser module and focusing optics, a hybrid machining head, a pulsed voltage source, an electrolyte supply and handling systems, a special tubular electrode, a LabVIEW®

based control unit and the machining cell. Table 1 lists the specifications of this in-house developed prototype hybrid machine-tool.

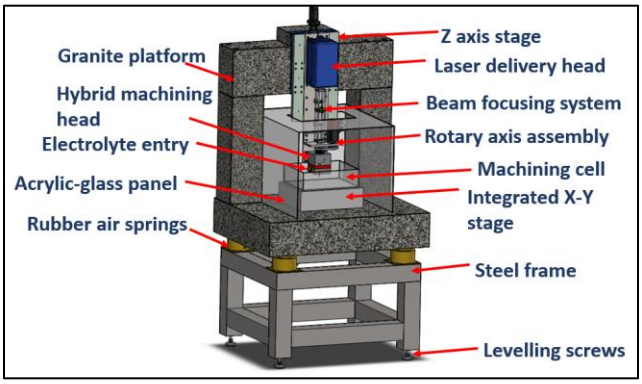

Figure 2. CAD model (top) and actual picture (bottom) of the in-house developed hybrid laser-electrochemical micromachining setup.

The system has a close gantry frame design with flatness (<5 um) and perpendicularity (<20 um) as specifications. The machine frame is supported by a steel frame on rubber air springs for passive vibration isolation. The motion stages are driven by DC servo motors with precision ball screws and precision mechanical bearing stages with a resolution of 0.1 µm and repeatability of ± 0.2 um. The stages are equipped with a Renishaw® encoder and scale (receiver frequency 20 MHz). A hybrid machining head (dimensions: 100x115x115 mm^3) is designed in-house to combine laser and electrochemical process energies along the same machining axis. The electrolyte enters radially into the machining head and the laser enters vertically into the spindle through a sapphire window. The spindle is supported on a pair of hybrid angular contact ball bearings with ceramic balls and steel races for electrical isolation. Carbon brushes with 50% silver content are mounted to transfer current to the spindle with minimal voltage drop at the point of contact. An AC servomotor (nominal torque: 1.27 Nm) is used as a rotary drive and connected to spindle via 1:1 toothed belt-pulley drive. The tool is a stainless steel (EN1.4301) tube with an inner concentric layer of quartz glass capillary to increase the acceptance angle of light into the electrode. The tool acts as a leaky mode waveguide for the 532 nm laser. The high frequency short-pulsed voltage pulses are derived by switching on-off a DC voltage source using an NMOS switch. The interelectrode gap is set manually using electric touch.

A pulsed laser (avg. power 30 W, ns pulsed, max. pulse repetition rate: 1500 kHz, max. pulse energy 180 uJ) of 532 nm wavelength is used on the equipment. A green laser is used as it has little absorption (α: 0.045/m) in pure water [Pope, 1997]. The control and data acquisition is realized with a NI® CompactRIO system. The electrolyte supply and handling system mainly consist of an AC motor driven gear pump controlled by a frequency regulator and is connected to a two-way valve for flexibility in switching different electrolytes. The electrolyte is filtered using a 1 µm absolute filter to prevent the suspended salt particles entering in the path of laser. The equipment also has several add-on modules such as a CCD camera for characterizing laser intensity in the electrolyte, a laser power meter and thermopile sensor, a temperature measurement module and a hall current sensor to measure the machining current.

Table 1: Specifications of the hybrid laser-electrochemical equipment.

Module	Specifications
Granite gantry frame	Closed frame gantry type, material: granite, overall dimensions: 1100 x 1000 x 800 mm, weight: 850 kg, perpendicularity < 20 µm and flatness < 5 µm (on specs).
Motion stages	DC servo motor driven, precision ball screw, stroke: 150 mm, resolution: 0.1 µm, accuracy: ± 2 µm, repeatability: ± 0.2 µm, Renishaw® encoder and scale (receiver frequency 20 MHz).
Rotary axis	AC servomotor driven (Nominal torque : 1.27 Nm), 1:1 toothed belt-pulley drive.
Laser module	Wavelength: 532 nm, pulse duration: 3-50 ns, average power: 30 W, max. repetition rate: 1500 kHz, max pulse energy: 180 µJ.
Pulsed voltage source	Voltage: 0-30 V, Current: 5A (max), Pulse on time: 1µs – 1ms, connecting loop: 100 cm², duty cycle: 0-50 %.
Hybrid machining head	Dimensions: 100 x 115 x 115 mm, two part design, supported on hybrid angular contact ball bearings, current connection via carbon (50% Ag) brushes.
Electrolyte supply and handling unit	AC motor driven gear pump, pump control by frequency regulator, 1 µm absolute filter, two way inlet.
Control	PC based control via NI®CompactRIO module, HMI on LabVIEW.
IEG detection	Electric touch based

3. Experimentation

In order to investigate the effectiveness of the hybrid laser-electrochemical micromachining process, experimental investigations were carried out using the in-house developed prototype machine-tool as discussed in the previous section. Table 2 shows the process parameters used in the preliminary experiments.

Three sets of experiments were designed: only electrochemical micromachining and laser assisted electrochemical micromachining with laser pulse energies corresponding to two different parameter sets. Three samples were machined using each technology for effective comparison. The effective laser pulse energies available for machining (after travelling through the electrolyte) were evaluated using a thermopile sensor from Ophir®. These measurements were realized by passing the laser through 20% w/v aq. NaNO3 solution filled up to a height of 70 mm and a 3W absorption of laser power was observed. This does not take into account the laser power absorbed inside the tube electrode after each reflection. The electrolyte conductivity was measured using a Greisinger® conductivity meter to be 137.8 mS/cm at an electrolyte temperature of 19.3 ^{0}C. The machining time was fixed to 30 s for all the experiments and point removals were analyzed.

Table 1: Process parameters used in the preliminary experiments.

Parameter	Value
Voltage	20 V
ECM pulse on time & duty cycle	10 µs, 50%
IEG	20 µm
Electrolyte	200 g/l $NaNO_3$ solution
Electrolyte flow rate	~2.4 l/h
Electrolyte conductivity	137.8 mS/cm @ 19.3 ^{0}C
Laser parameters corresponding to pulse energy 100 µJ	Pulse duration: 15 ns, Pulse repetition rate: 250 kHz, Average power 25 W
Laser parameters corresponding to pulse energy 167.67 µJ	Pulse duration: 50 ns, Pulse repetition rate: 150 kHz, Average power 24 W

The workpiece material is Inconel IN718 super alloy of 3.17 mm thickness. IN718 was selected because of its difficult machinability by conventional machining methods (due to its high hardness: 25-38 HRC depending on the heat treatment). Laser machining and EDM can machine Inconel but the workpiece is prone to thermal damage. ECM has been investigated before to machine Inconel 718 but the process suffered with low material removal rates and also locally varying current densities due to the microstructure.

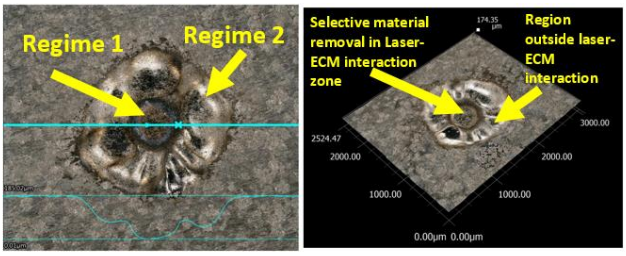

Figure 3. Optical images (Keyence®) showing a cavity machined by hybrid laser-ECM process. (Parameters: Refer table 1 and laser pulse energy: 167.67 µJ).

4. Results and discussion

4.1. Machined surface

Figure 3 shows a cavity machined by hybrid laser-electrochemical micromachining with the parameters mentioned in image caption. Two different regimes can be clearly distinguished. Regime 1 corresponds to the zone of laser-electrolyte interaction, being of the order of the internal diameter of the tubular electrode through which both laser and electrolyte pass. Regime 2 corresponds to the area just below the conductive area of the tubular electrode i.e. the regime outside the direct interaction of laser with the electrolyte. It can be observed that the assistance of laser to electrochemical machining increases the rate of chemical reactions thereby accelerating the material removal in regime 1. In Figure 3, the cavity depth is higher in regime 1 as compared to regime 2.

4.2. Material removal rate

Figure 4 shows the comparison of average volumetric material removal rates of ECM and hybrid laser-ECM. The volume of the machined cavities has been estimated using the point cloud data of a 3D surface scan acquired using a Keyence® VHX6000 microscope. It can be observed from Fig. 4 that the assistance of laser improves the material removal rate. This is due to the temperature induced rise in the rate of electrochemical reactions. For the specific set of experiments performed here, a 7% and 9.5% rise in average volumetric MRR has been observed (Figure 4) for laser pulse energies 100 and 166.67 µJ respectively. The improvement in the material removal rate is less than expected. This is because a large portion of heat on the workpiece surface is lost due to convection by the pressurized electrolyte impinging on workpiece surface as well as by absorption during reflections inside the tubular electrode and by scattering with salt particles. These power losses are difficult to characterize experimentally and require more modelling efforts. Thus, only a small amount of power is actually utilized in heating up the machining zone.

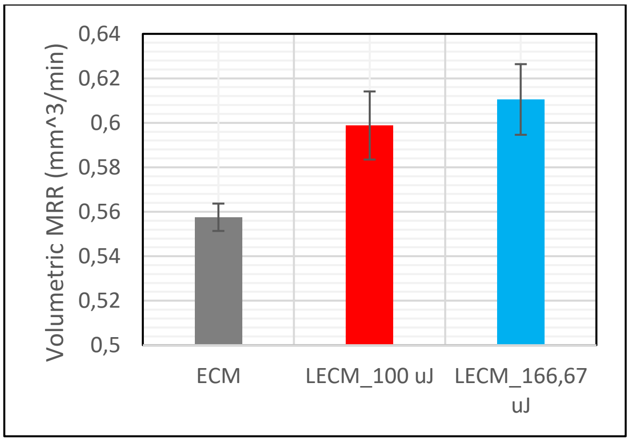

Figure 4. Comparison of average volumetric MRR for ECM and hybrid laser-ECM process.

4.3. Machining current

Figure 5 shows the range of mean currents observed during machining for all three samples (named here: S1, S2, S3) machined using ECM and Laser-ECM at two different pulse energies. The current data were acquired using a hall current transducer (response time of 3 µs) calibrated using a Tektronix TCP-202 current probe. It can be clearly observed from Fig. 5 that the range of machining currents observed with the laser-ECM process is higher than for the ECM process. A further rise was seen in the increase in range of machining currents when the laser pulse energies were increased from 100 to 167.67 µJ . This can be explained on the basis of Arrhenius equation (Eq. i) for chemical reactions [5] .

$$j = k_a C_R exp\left(\frac{-E_a}{RT}\right) \qquad \text{(i)}$$

where, j denotes current density, k_a: anode process constant, C_R : reducing concentration constant, E_a: activation energy, R: gas constant, T: reaction temperature. It is evident from Eq. (i) that when the reaction temperature increases, the current density increases and the material removal is faster. In hybrid Laser-ECM process, the laser acts as a localized heat source and increases the temperature in the localized zone. This results in higher machining currents.

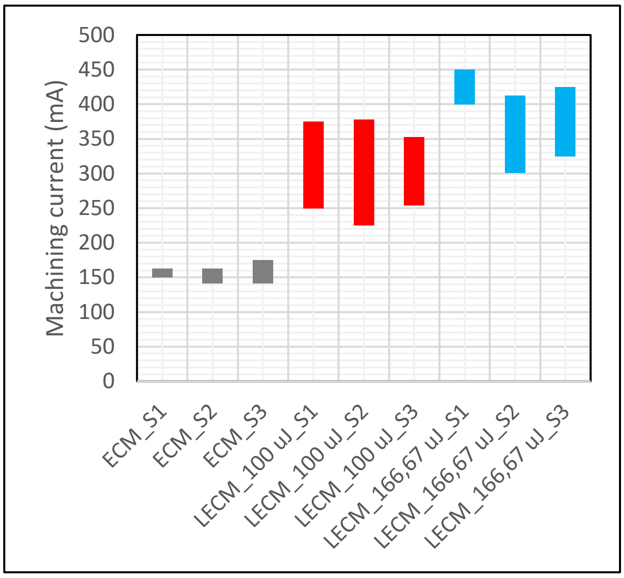

Figure 5. Range of mean machining currents observed during ECM and hybrid Laser-ECM process.

4.4. Surface quality

In order to characterize the surface roughness in different zones of the machined surfaces obtained from the hybrid laser-ECM process, the cavities were examined under a Sensofar® lynx microscope. The surface- roughness values were measured for both regime 1 and regime 2 (refer to Fig. 3). Regime 1 corresponds to the localized zone processed dominantly with hybrid laser-ECM process and regime 2 corresponds to the region outside the localized area where the laser-ECM interaction effect is less pronounced. The roughness values were measured using confocal imaging technology, a 50x objective, an acquisition area of 120.86 x 123. 05 µm, a cut off wavelength of 25 µm [ISO 16610-61, ISO 25178-2]. The surface roughness measurements were carried out on the three samples processed by the same hybrid laser-ECM process with laser pulse energy 167.67 µJ (Other parameters are the same as in Table 2).

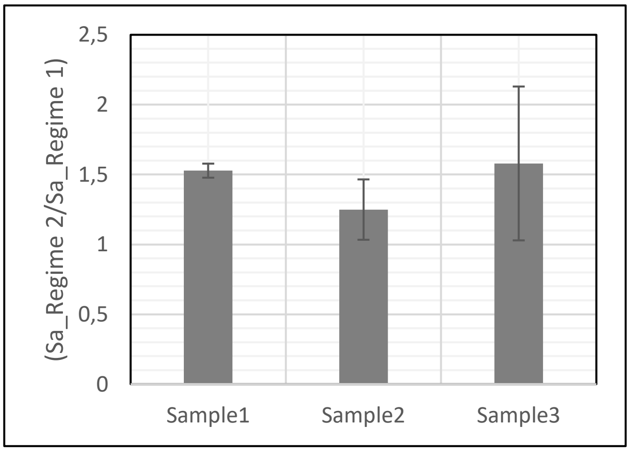

Figure 6. Plot of ratio of *Sa* in regime 2 vs regime 1 for three samples machined using hybrid laser-ECM process with pulse energy 167.67 µJ.

Three measurements were taken in both regime 1 and regime 2 for each sample and average values are taken as the representative *Sa* value. The error bars represent one standard deviation between the three measurements. The local sparking zones and regions of noise were excluded from roughness measurements. Figure 6 shows the plot with the ratio of *Sa* for regime 2 vs regime 1 for all the three samples. It can be observed that the surface quality is higher in regime 1 as compared to regime 2. This can be explained based on ECM literature stating that higher current densities lead to better surface finish [6]. In regime 1, the current densities are higher (due to a higher temperature) and hence surface finish is better as compared to the surface in regime 2. Figure 7 shows a representative image for both regime 1 (*Sa*: 99.68 nm) and regime 2 (*Sa*: 200 nm) from sample 2 acquired using confocal imaging technology. It can be observed that the surface corresponding to regime 1 is much cleaner and smoother as compared to the surface corresponding to regime 2.

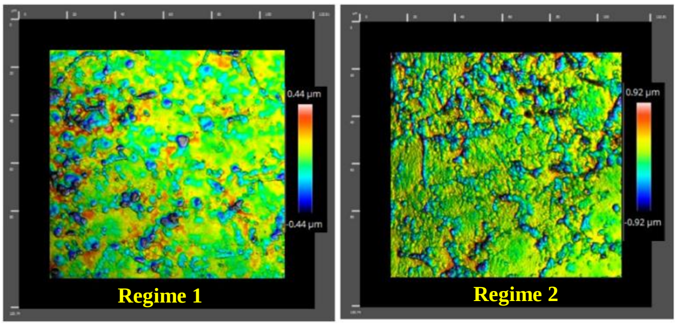

Figure 7. Confocal images showing 2D surface topography of regime 1 and regime 2 in the cavity machined using hybrid laser-ECM process with pulse energy 167.67 µJ. (Acquisition area: 120.86 x 123. 05 µm).

5. Concluding remarks

In this work, a novel configuration of a hybrid laser-electrochemical micromachining process and the development of the accompanying prototype machine tool is presented. Preliminary experimental investigations reveal an improvement in volumetric material removal rate due to a temperature induced increase in local current densities. Higher machining currents are observed during hybrid laser-ECM micromachining. There is an improvement in surface finish of those regions which are predominantly exposed to hybrid laser-electrochemical micromachining.

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References

[1] Lauwers, B., Klocke, F., Klink, A., Tekkaya, A. E., Neugebauer, R., and McIntosh, D., 2014, Hybrid processes in manufacturing, CIRP Ann. - Manuf. Technol., **63**, pp. 561–583.

[2] Saxena, K. K., Bellotti, M., Qian, J., Reynaerts, D., Lauwers, B., and Luo, X., 2018, Ch 2: Overview of Hybrid Machining Processes, In Book: Hybrid Machining-Theory, Methods, and Case Studies, Elsevier Ltd, pp. 21–41.

[3] Saxena, K. K., Bellotti, M., Van Camp, D., Qian, J., and Reynaerts, D., 2018, Ch 5: Electrochemical Based Hybrid Machining, In Book: Hybrid Machining-Theory, Methods, and Case Studies, Elsevier Ltd, pp. 111–129.

[4] Saxena, K. K., Qian, J., and Reynaerts, D., 2018, A review on process capabilities of electrochemical micromachining and its hybrid variants, Int. J. Mach. Tools Manuf., **127**, pp. 28–56.

[5] De Silva, A. K. M., Pajak, P. T., Harrison, D. K., and McGeough, J. A., 2004, Modelling and experimental investigation of laser assisted jet electrochemical machining, CIRP Ann., **53**(1), pp. 179–182.

[6] Kawanaka, T., Kato, S., Kunieda, M., Murray, J. W., and Clare, A. T., 2014, Selective surface texturing using electrolyte jet machining, Procedia CIRP, **13**(October), pp. 345–349.