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Evaluation of surface quality and process hybridisation in electrochemical layered manufacturing process

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Abstract

Electrochemical additive manufacturing (ECAM) is a localised version of electroplating, where material is deposited through accretion on a cathodic substrate using a suitable electrolyte and anodic tool electrode under an applied voltage/current. The process has the capability to deposit layers of multi-materials on metallic mechanical parts for enhanced functionalities and hence, is also referred to as electrochemical layered manufacturing process. Depending on the mode of electrolyte supply (bath, jet, meniscus) and type of tool, it can deposit 2D-3D features from nm-mm scale with a varying degree of surface and dimensional quality. Due to the non-contact and athermal nature of the process, the deposits are free from thermal defects and material properties are preserved. As ECAM is essentially the reverse of electrochemical machining (ECM), it is convenient to implement the two processes together in a hybrid process chain.

In this work, an ECAM process is presented which has the capability to perform localised electrochemical layered manufacturing and machining. The results on surface quality and process hybridisation with ECM are presented with a discussion on process sequence and parameters influences. Using a wire electrode suspended inside a plastic nozzle with a low flowrate electrolyte, it was possible to deposit a L-shaped copper (Cu) feature on a stainless steel (S.S.) substrate with a surface quality of 0.38 ± 0.02 µm and material deposition rate of (MDR) of 16.06 µg/s.

Electrochemical additive manufacturing, electrochemical machining, additive manufacturing, micromachining, process hybridisation

1. Introduction

Additive manufacturing (AM) is gaining increased traction in the manufacturing industry due to its capabilities of producing complex near net shape parts with hollow internal structures which are expensive or difficult to manufacture with conventional processes. Laser based AM processes have achieved a major foothold in AM research and industry however, they require a controlled environment and the thermal load from the laser results in parts with rough surfaces, porosities and internal stresses which requires post processing [1]. Electrochemical additive manufacturing (ECAM) or EC layered manufacturing is a localised version of electroplating which can deposit 2D-3D structures in an open environment [2]. The athermal and noncontact nature of the process results in deposited parts which are free from thermal defects with preserved material properties and minimal post processing needs. The dimensions of ECAMed parts range from nm-mm [3] depending on the flow mode and nozzle size. Meniscus confined ECAM (MECAM) can deposit precise features with good surface quality (<0.5 µm *Sa*) but the process is quite slow (~0.8 µg/s at 5 V and 0.1 mm/s) [4] and not suitable for volume production. Jet-ECAM (JECAM) on the other hand, is suitable for rapid prototyping but the high speed electrolyte jet (20-50 m/s) which controls the spread of current density, disturbs the deposition quality and localisation. Research is being done to improve the precision without compromising the deposition rate through additional external controls like masking, air flow [2] and liquid confinement [5]. In this research, a low cost ECAM process is presented which can achieve localised deposition through the combination of a plastic nozzle, suspended anode wire and low flow speed (<2 m/s). Additionally, since ECAM is the reverse of electrochemical machining (ECM) which can machine conductive materials independent of hardness [6], the two processes can be hybridised into a process chain [7] to tackle the demands for multifunctional components and features on difficult-to-machine materials. The potential applications include repair of minor cracks and surface damages, creation of functionally graded surfaces, tolerance correction, printing sensors on machined parts, electrically connecting smart textile peripherals and prototyping of miniature parts.

This paper briefly discusses the performance of the developed process along with sequence and process parameters influence on the hybridised process chain.

2. Experimentation

2.1. Experimental Setup

The setup was developed in-house by modifying a Prusa® i3 MK3S 3D printer to perform ECAM and ECM as shown in Figure 1a. Electrolyte continuously flows through or is held in a meniscus under a 400 µm internal dia. (I.D.) plastic nozzle. A 350 µm dia. copper (Cu) wire electrode suspended inside the plastic nozzle controls the current density distribution (Figure 1b). The interelectrode gap (IEG) is set by detecting the workpiece surface by piezo-buzzers (repeatability of 7 µm) embedded under the manufacturing cell. A Tektronix® direct current (DC) power supply (PWS4305) provides the voltage to the circuit whereas, a polarity switch is employed to switch between the ECM and ECAM processes.

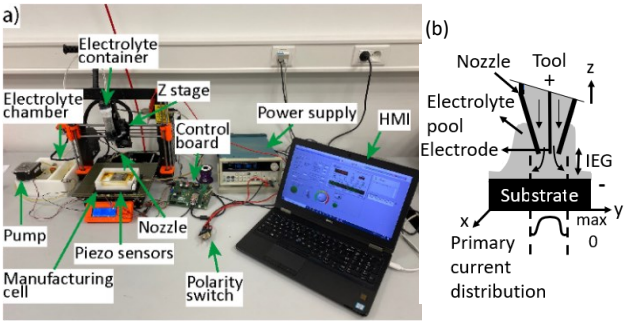

Figure 1: a) Experimental setup with major peripherals, b) Process schematic and current density distribution.

2.2. Materials and process parameters

To study the process compatibility of ECM and ECAM along with surface quality and deposition localisation, 'L' shaped Cu features were deposited on a S.S. (EN-1.4301) substrate and the substrate itself was machined with ECM. The samples were immersed for cleaning in deionized water for 10 mins.

Table 1: Process parameters.

Parameters	Value
Voltage	5 V (ECAM), 20 V (ECM)
Scan rate	0.1 mm/s (ECAM), 0.8 mm/s (ECM)
Scan layers	10
Initial IEG	80 µm
Electrolyte flow rate	8 mL/min

Table 2: Electrolytes.

Electrolyte	Properties (Conc., conductivity)
aq. $CuSO_4$ (µECAM)	1 M, 40 mS/cm at 19 °C
aq. NaCl (µECM)	2.5 M, 110 mS/cm at 19 °C

3. Results and discussion

The localised deposited Cu feature shown in Figure 2b had minimal stray deposition and sharp edges with an average width of 532.32 ± 33 µm, which is 33 % higher than the nozzle I.D. The higher over-deposition is expected which can be controlled by the applied voltage level and is not necessarily an indication of poor localisation since the aim is to reduce stray deposition and improve precision, which is evident from the straight features and low deviation in width. The cross-sectional profile (Figure 3b) also indicated the current density distribution was centred under the electrode and localised by the plastic nozzle to reduce the lateral spread. There were also no deviations at the corners where the scanning direction changed. The surface roughness (Sa) (Sensofar® Neox, ISO 16610-61, long wavelength L-filter of 8 µm, short wavelength S-filter of 0.8 µm and 20x objective) was measured with an acquisition area of 250 x 250 µm and is shown in Figure 3a. The Cu deposit had a similar *Sa* of 0.38 ± 0.02 µm as MECAM (0.32 ± 0.03 µm) [4] but with 20 times higher MDR (16.06 µg/s). The machined ECM L-groove was also localised with a 148 % higher width than nozzle I.D. due to higher voltage.

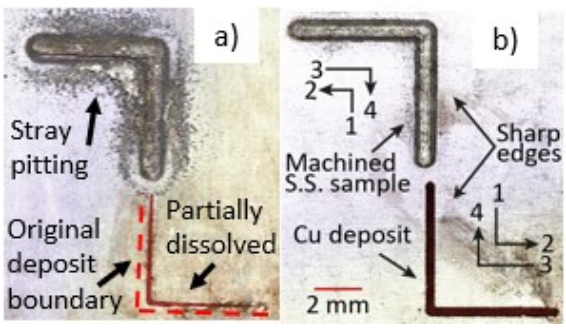

Figure 2: a) ECM after ECAM, b) ECM before ECAM.

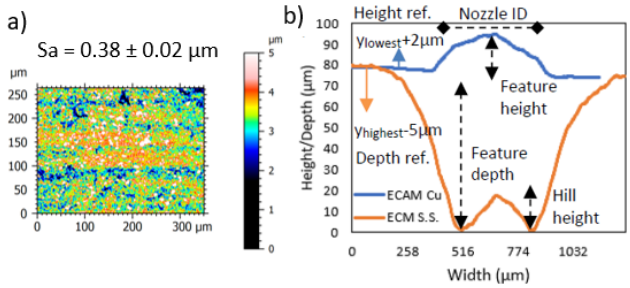

Figure 3: a) Surface topography of Cu deposit, b) Cross-sectional profiles (blue-ECAM, orange-ECM).

The results of Figure 2 indicate that the process sequence and parameters are important. If incompatible parameter combination of voltage and flow rate is used for ECM, it results in considerable stray removal. Additionally, if ECM is performed after ECAM the higher voltage results in partial dissolution of the more reactive Cu deposit, even at locations 6 mm away from the ECM machining zone. For the case of ECAM after ECM, the features were preserved but the ECM feature had a small undissolved hill (20.8 ± 8 µm height) due to by-products accumulation in the gap which required higher flow rate for flushing. Hence, it is important to consider the process sequence and ECAM after ECM results in a good process chain. However, it also limits the processing capabilities and requires additional research into material/process compatibility and feature isolation to allow bi-directional process chains for advanced applications.

4. Conclusion

The developed ECAM process can deposit features with good surface quality (0.38 ± 0.02 µm) comparable to MECAM but 20 times higher MDR without compromising deposit localisation. The ECAM after ECM process sequence resulted in preserved features but the reverse sequence partially dissolved the Cu deposit due to the higher ECM voltage and Cu reactivity. The setup will be further developed to improve individual process capabilities and facilitate bi-directional hybrid process chains.

Acknowledgement

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References

[1] J. Metelkova, L. Vanmunster, H. Haitjema, *et al.*, "Hybrid dual laser processing for improved quality of inclined up-facing surfaces in laser powder bed fusion of metals," *J. Mater. Process. Technol.*, vol. 298, no. March, p. 117263, 2021.

[2] L. Xinchao, M. Pingmei, A. Sansan, and W. Wei, "Review of additive electrochemical micro-manufacturing technology," *Int. J. Mach. Tools Manuf.*, vol. 173, no. July 2021, 2021.

[3] Braun T. M. and Schwartz D. T., "The Emerging Role of Electrodeposition in Additive Manufacturing," *Electrochem. Soc.*, vol. 25, no. 1, pp. 69–73, 2016.

[4] M. H. Arshad, K. K. Saxena, R. Smith, J. Qian, and D. Reynaerts, "Localized and Mask-less Copper Deposition with Free-flow Jet micro-ECAM," *Int. J. Electr. Mach.*, vol. 27, p. 16-21, 2022.

[5] X. Chen, J. Chen, K. K. Saxena, J. Zhu, X. Gu, and Z. Guo, "Localization of jet electrochemical additive manufacturing with a liquid confinement technique," *J. Manuf. Process.*, vol. 81, no. June, pp. 48–64, 2022.

[6] A. Speidel *et al.*, "Electrochemical jet manufacturing technology: From fundamentals to application," *Int. J. Mach. Tools Manuf.*, vol. 180, no. July, p. 103931, 2022.

[7] J. Mitchell-Smith, A. Speidel, I. Bisterov, and A. T. Clare, "Electrolyte Multiplexing in Electrochemical Jet Processing," *Procedia CIRP*, vol. 68, no. April, pp. 483–487, 2018.