“Electroforming 4.0” – Significance, challenges & optimisation

Corresponding Author: Eleni Andreou, University of Strathclyde, James Weir Building, Department of Chemical & Process Engineering, eleni.andreou@strath.ac.uk

Co-author: Sudipta Roy, University of Strathclyde, sudipta.roy@strath.ac.uk.

Since the concept of “Industry 4.0” was introduced, the most competitive industrial manufacturers around the world have been trying to secure sustainable, high quality, low-cost technological developments. Alongside the total computerisation of manufacturing and fabrication, new manufacturing technologies will need to arise to replace traditional production lines with more flexible ones able to support the evolved industrial needs of the next transition.

Among these technologies, additive manufacturing processes have significantly contributed to the rapid transformation of the industrial landscape during the last decade. In particular, “low-volume/high-value" industrial sectors, such as the aerospace, marine and energy industries, are expected to benefit from this kind of approaches. This is mainly because manufacturing of larger volumes of customised products could be achieved in that manner, followed by a reduction of industrial and economic waste, decrease in the cost of operation and reduction of environmental impact.

Electroforming is increasingly gaining recognition as a promising and sustainable additive manufacturing process of the “Industry 4.0” era. Numerous important laboratory-scale studies try to shed light onto the pressing question as to which are the best industry approaches to be followed towards the process’s optimisation. However, for electroforming to be successfully optimised and efficiently applied in industry, systematic scale up studies need to be conducted. Well-informed simulations can provide a much-desired insight into the novelties and limits of the process, and therefore, scaling up modelling studies are of essence.

Additive-free nickel electroforming, in particular, could also play an important role in the much-desired “green” transition of lightweight manufacturing. Even within the currently available infrastructure, the same electroforming reactors can remain in use for years if properly maintained, the stainless-steel cathodes (mandrels) and titanium anode baskets are re-usable and recyclable, while process efficiency (especially for sulphamate baths) is usually close to 100%. Hazards arising from the use of nickel can easily be mitigated, while developments on nickel recovery and recycling are increasingly promising.

Modelling studies can help further, towards process optimisation at all three (system, process and product) sustainability levels. Since electroforming’s final products can be of various scales and requirements, well-informed modelling studies could assist with efficient tooling and process design for different cases. That way, key process parameters, such as the deposition duration, applied currents, heating and agitation requirements, or even quantitative material requirements, could be finetuned on a case-by-case basis.

Therefore, to better understand the process and its potential, a systematic nickel electroforming modelling approach was followed; starting from primary current distribution (PCD) simulations which depend solely on the system's geometry, moving forward to introducing kinetic contributions through secondary current distribution (SCD) studies and, finally, developing tertiary current distribution (TCD) models completed by the introduction of mass transfer effects.

In practice, time-dependent nickel electroforming models of different scales were developed and studied using COMSOL Multiphysics®, a finite element method commercial software. The models were experimentally validated. Electrochemical experimental data, collected via polarisation studies, were used as input for the models. The boundary conditions at the cathode and anode were based on the overall nickel reduction and dissolution reactions, respectively. Current-potential data was used to fit the exchange current density, equilibrium potential, limiting current, as well as anodic and cathodic charge transfer coefficients.

Modelling and experimental results were interpreted in terms of the deposit thickness distribution and uniformity. PCD modelling offered a preliminary insight into the system's electrochemical behaviour, confirmed the direct relation between current and thickness distribution, and highlighted the dependence of the simulated results on the setup's geometrical configuration. SCD simulations were subsequently used for mesh, geometry, and kinetic sensitivity studies, to be followed by TCD simulations involving multiple species and reactions.

These studies confirmed that commercial simulation software can reliably model precision electrodeposition processes, such as electroforming. At the same time, the models' credibility is dependent on good quality input parameters, derived through practical experiments. Among other observations, simplified SCD models were proven to be efficient in modelling processes not affected by tertiary phenomena. Targeted investigations on how the size, geometry and configuration of an electroforming reactor can affect the final product suggested time- and cost-effective modifications of the setup itself which can lead to process optimisation. Overall, computational studies allowed for the development of a study approach aiming to optimise both electroforming simulations and application in production lines.