

Analysis of Complex, Beam-Sensitive Systems by Electron Microscopy

Martha Ilett¹, Helen Freeman¹, Zabeada Aslam¹, Maryam Afzali¹, Joanna Galloway², Fiona Meldrum² and Rik Brydson^{1*}

¹. School of Chemical and Process Engineering, University of Leeds, Leeds LS2 9JT, UK.

². School of Chemistry, University of Leeds, Leeds LS2 9JT, UK.

* Corresponding author: mtlrmdb@leeds.ac.uk

Complex, electron-beam sensitive systems include organic crystals, polymers, hybrid organic-inorganic materials, some inorganic materials such as hydrates, as well as multiphase solid/liquid and solid/gas systems. Arguably they constitute the majority of systems of current interest across a wide range of scientific and engineering disciplines. We review the use of analytical transmission electron microscopy (TEM) for the characterisation of such beam-sensitive materials and complex, multiphase systems *in-situ* or close to their native state. Such materials are prone to damage by radiolysis which cannot be eliminated or switched off, requiring TEM analysis to be done within a dose budget so as to achieve an optimum dose-limited resolution and reliable, artefact-free results [1]. We highlight the importance of determining the damage sensitivity of a particular system in terms of characteristic changes that occur on irradiation under both an electron fluence and flux. We discuss the choice of electron beam accelerating voltage and detectors for optimizing resolution and outline the different strategies employed for low-dose microscopy in relation to the damage processes in operation. In particular, we discuss the use of scanning TEM (STEM) techniques for maximizing information content from high-resolution imaging and spectroscopy of materials and the use of cryogenic sample preservation methods.

As an example, we describe studies of crystallization processes in the calcium sulfate system using a correlated approach: a combination of liquid cell TEM (LC-TEM), *in-situ* Raman spectroscopy and cryogenic TEM (cryo-TEM). Recent studies have suggested that the calcium sulfate polymorph gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) can form in aqueous solution via a bassanite ($\text{CaSO}_4 \cdot 0.5\text{H}_2\text{O}$) intermediate. Hence, initially we studied the transformation of bassanite nanorods to gypsum in an undersaturated aqueous solution of calcium sulfate. When coupled with Raman spectroscopy, the real-time data generated by LC-TEM, and structural data obtained from time resolved cryo-TEM (i.e. crystallising solution samples vitrified at various time points) showed that bassanite can transform to gypsum via multiple pathways, the predominant one being dissolution/reprecipitation as opposed to the oriented attachment of nanorods and subsequent solid state transformation. Comparisons between LC-TEM and cryo-TEM also showed significantly reduced kinetics within the confined liquid cell as compared with bulk solution, however the electron beam induced radiolysis of water (so lowering the local pH) can accelerate the transformation process [2]. Further studies focused on the direct formation of gypsum from aqueous solution using a range of different sample preparation methods: drop casting of solutions and drying, vacuum filtration, chemical quenching and drop casting, time-resolved cryogenic freezing, as well as LC-TEM. Here we suggest that the observed crystallization pathway can be highly dependent on the degree of supersaturation experienced during the sample preparation method, which may lead to highly erroneous observations.

References:

[1] M. Ilett et al., *Phil. Trans. R. Soc. A* 378: 20190601 (2020). doi:10.1098/rsta.2019.0601.

[2] M. Ilett et al., *J. Microscopy* 2022, accepted.