Micro-CT as a 3D reverse engineering tool to study emulsification processing

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Introduction

The goal of reverse engineering is to reproduce, duplicate, or enhance products and systems based on the study of an original object/system without drawings, documentation, or a computer model[1]. It's also called back engineering and is used in many application areas, such as manufacturing, industrial design, digital archiving, electronics, dental or surgical prosthetics and competitor analysis. In emulsion manufacturing two immiscible liquids are mixed using in-line high shear rotor-stator mixers. They are used for products such as shampoos, deodorants, salad dressings and sauces. The droplet size of these products influences the stability and rheological properties of these products. Generally, the smaller the average particle size and the tighter the size distribution, the more stable the emulsion. Sufficient mixing energy is required in order to create small droplets in an emulsion. These mixers consist of a rotor and stator that have concentric rows of intermeshing teeth[2]. This rotor-stator combination is called the mill head. The product enters at the centre of the stator and moves outward through radial channels in the rotor/stator teeth. The combination of high tip speed and extremely close tolerances subjects the product to intense shear in every pass. The gap between adjacent surfaces of the rotor and stator is adjustable for fine-tuning shear levels and flow rates. Knowledge is needed of the detailed geometry of rotor-stator mixers to obtain hydrodynamic insight in the emulsification process. The geometric size and shape or complete 3D geometric models can be used as input for computational fluid dynamic (CFD) studies)[3]. Reverse engineering often involves disassembling and analysing its components and workings in detail. In this study X-ray microtomography (micro-CT)[4] is used for the non-invasive visualisation and analysis of the size and shape of rotors and stators. To prevent disassembling, micro-CT images were made of silicone "negatives" (or "moulds") of the rotors and stators. The results were compared to those obtained by profilometry of the original object.

Method

A silicon mould was made of a mill head using the following procedure:

- A silicone-based lubricant was sprayed onto the rotor/stator head, which produces a very thin layer.
- Then a "negative" or "mould" of the rotor/stator was made by filling it with pourable silicone (2-component Silicone RTV 664, *https://www.momentive.com/products/show-technical-datasheet.aspx?id=26640*) and letting this solidify overnight in an oven at 70 °C.
- After solidification of the silicone, the mould was carefully removed. Then a representative piece was cut out that fits the sample holder of the micro-CT (Figure 1). Plastic cylindrical sample holders with an inner diameter of 27 mm were used. The upper part of the sample holder consist of a removable open tube with a length of ~60 mm.

This mould was imaged using a Skyscan 1172 desktop micro-CT system with a 100kV X-ray source (10W, 20-100kV, 0-250µA, < 5µ spot size) and a 10 Mp X-ray detector (4000 * 2096 pixels). Power settings of 95kV and 104µA were used. Images were acquired using a aluminium beam filter, step size of 0.23º over 180 degrees and frame averaging of 3. Scans with pixel sizes of 7.92 µm were made. The total scanning time (1800 images) was 6:16 hours/scan. The sample was scanned using 3 scans, connected in the vertical direction to increase the axial field-of-view (oversized scan) and subsequently merged together during the reconstruction. A stack of 5342 horizontal cross sections with a pixel size of 4000x4000 was obtained after tomographic reconstruction of the projection images. A beam hardening correction of 40% and ring artefact correction of 20 and smoothing of 4 were selected.

For quantitative analysis and visualisation in 3D space of the micro-CT images the AvizoFire 8.1.1 software from the FEI Visualization Sciences Group was used. The sizes were analysed using interactive measurement tools.

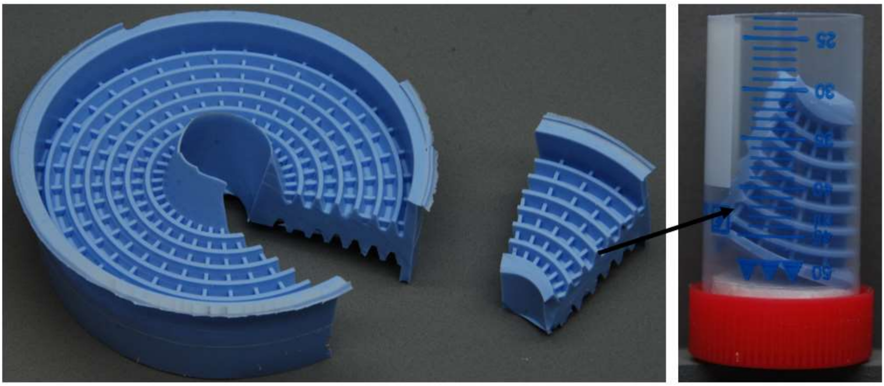

Figure 1 Sampling of a silicon mould of a rotor-stator mixer.

Profilometry was performed at the “Zeiss Measuring House” in Best (The Netherlands). Stylus profilometry refers to scanning the surface or profile of an object in order to specify/quantify its shape. The traditional way is to carefully move a probe (“stylus”) across the surface in order to determine the 3D location of a series of points with respect to a chosen reference. The analysis was performed on a rotor and a stator (the original part, not the mould).

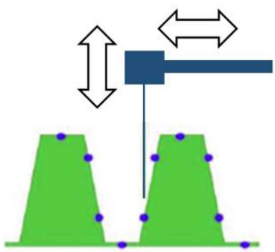

Figure 2 Schematic view of stylus profilometry of a mill head.

Results

Horizontal cross sections with 3D visualisations of micro-CT image of moulds of mill heads are shown in Figure 3. The mould is clearly visible as a dark object (white = low absorption coefficient) within the light grey sample holder. An example of the measurements of the width of the teeth and width of the gaps between the teeth (at their base and top) using a radial micro-CT cross section is shown in Figure 4. The measured values are constant over the total mill head (independent of the ring no). To calculate the actual dimensions, it has to be taken into account that the mould is the negative of the original object (Figure 5). The results of the analysis of a micro-CT image of a rotor are compared to those obtained by profilometry of the original rotor in Figure 6. The values for b, b', B + B', b + b' and H are within 2% relative. However larger deviations are seen for B and B'. For the latter cases, we have to realise that the measurements are made on the silicone moulds, so translated to that geometry the largest deviation is found in the top width B' of the mould teeth. This is the location where one would expect the largest effect of relaxation of residual elastic stresses in the mould after removal and/or the largest effect of shrinkage during curing. According to the RTV664 silicone information available on the Internet, this material has low shrinkage when cured at room temperature. All in all, we can thus conclude that the micro-CT values can be trusted quite well, although the individual values of B and particularly B' have to be used with some care. In order to develop this method further it would be worthwhile to spend some effort on the elimination of stress relaxation and shrinkage, by changing the curing temperature and/or by selecting a different type of mould material.

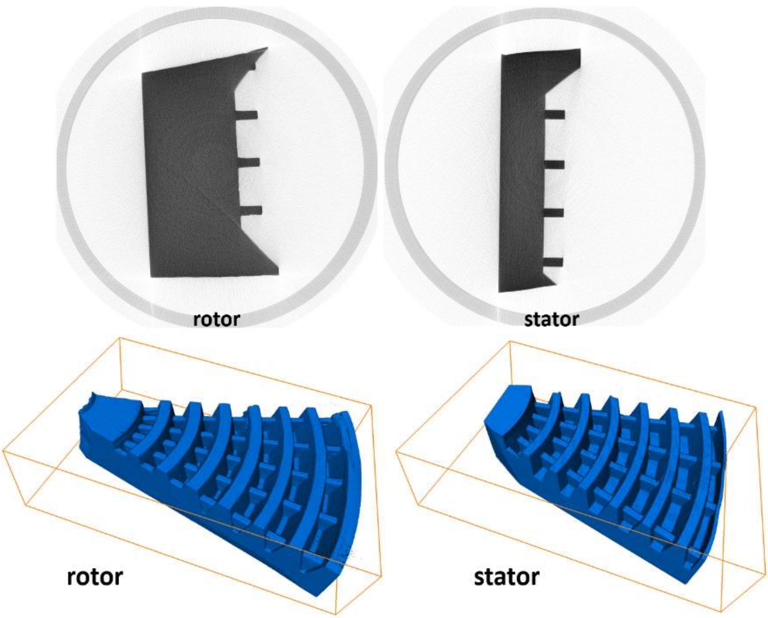

Figure 3 Horizontal cross sections (top) of micro-CT images of moulds of a rotor and stator (inner diameter of sample holder = 27 mm) with 3D visualisations (bottom: box size = 9mm x 26mm x 37mm).

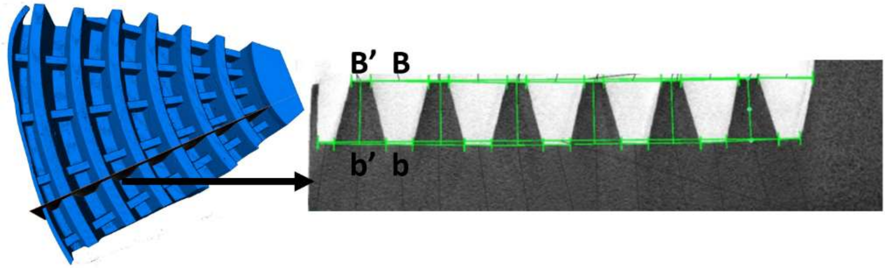

Figure 4 Example showing the measurement in the tangential direction of the mould of a stator).

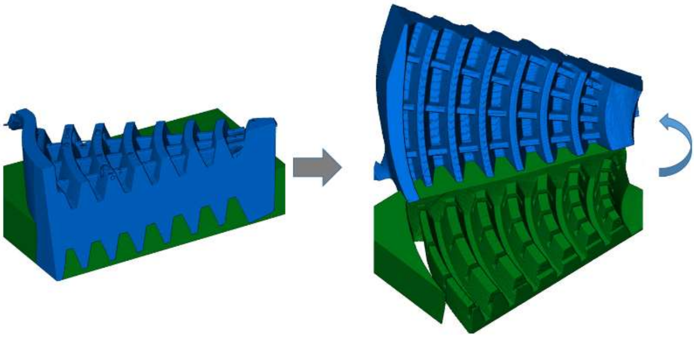

Figure 5 3D visualisation of the mould (blue) and the recalculated original (green).

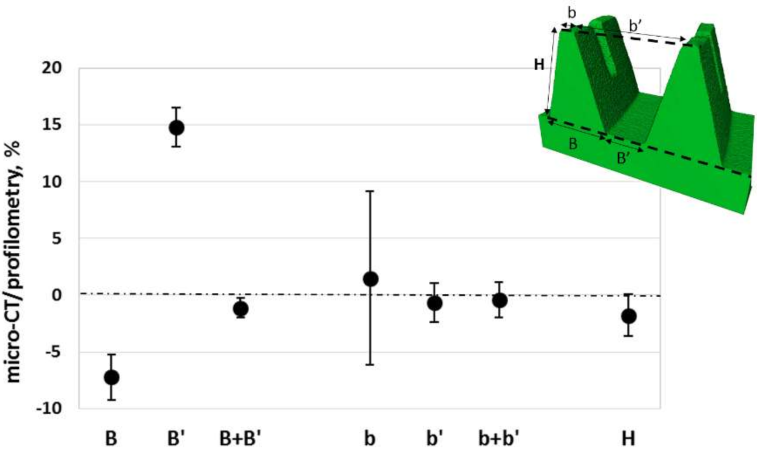

Figure 6 Comparison between the dimensions of a rotor measured by micro-CT and profilometry.

Conclusion

Micro-CT proved to be a very useful technique for non-destructive reverse engineering of complex objects such as stator-rotor mixers. Scanning a silicon mould of the original object is an effective method for accurate and precise 3D geometrical measurement. The results were for the most part well in agreement with profilometry of the original object. Remaining deviations can likely be explained from minor distortions to the mould during its solidification or after removal. Beside extracting the dimensions of the object also a complete 3D model can be generated which can be used as input for 3D modelling or 3D printing.

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3 Janssen, J.J.M. and Mayer, M. (2016) Computational Fluid Dynamics (CFD)-Based Droplet Size Estimates in Emulsification Equipment, Processes, 4, 50; doi:10.3390/pr4040050

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