INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED23
24-28 JULY 2023, BORDEAUX, FRANCE

APPLICATIONS OF ROTATIONAL MANIPULATORS IN THE MANUFACTURE AND CHARACTERIZATION OF HIGHLY CURVED THIN FILMS

McIntyre, Finn (1);
Sellier, Mathieu (1);
Gooch, Shayne (1);
Nock, Volker (2);
Sharplin, Nigel (3)

1: University of Canterbury, Mechanical Engineering Department;
2: University of Canterbury, Electrical & Computer Engineering Department;
3: Infact Limited, Christchurch, New Zealand

ABSTRACT

What do common devices such as smartphones, CD's and solar panels all have in common? They are all examples of innovative technology that is still limited to flat, rigid geometries. This is primarily due to the limitations of the manufacturing processes used to create components within these devices, key among them the thin polymer films produced through spin coating.

Spin coating is a technique used due to its ability to effectively create uniform films on the scale of micro or nanometres. However, it relies on a planar substrate to produce uniform layers, thus restricting the design of components manufactured using this process to simple, flat objects. As the requirement for curved device geometries expands, complex alternative fabrication methods are being implemented in industry.

For spin coating to remain relevant, a viable process for controlling the fluid flow over curved surfaces must be developed. This research investigates the hypothesis that coating distributions can be controlled through optimized rotation of a curved substrate. Where a multi-axis rotational manipulator and novel characterization system have been developed to investigate the fabrication of curved devices using the improved spin coating technique.

Keywords: Conceptual design, Early design phases, Mechatronics, Microfabrication, Spin Coating

Contact:
McIntyre, Finn
University of Canterbury
New Zealand
finn.mcintyre@pg.canterbury.ac.nz

Cite this article: McIntyre, F., Sellier, M., Gooch, S., Nock, V., Sharplin, N. (2023) 'Applications of Rotational Manipulators in the Manufacture and Characterization of Highly Curved Thin Films', in *Proceedings of the International Conference on Engineering Design (ICED23),* Bordeaux, France, 24-28 July 2023. DOI:10.1017/pds.2023.63

1 INTRODUCTION

Common devices such as smartphones, CD’s and solar arrays are examples of technology that has become available due to advances made in the microfabrication industry. However, they all share one key limitation: the geometrical arrangement of their key components is predominantly constrained to that of a flat, rigid object. This is because the manufacturing processes used throughout production are optimized around that same geometry, specifically the creation of thin films through the coating of a substrate. The main process used for this throughout industry is spin coating, as it is low-cost and highly effective at producing uniform films with excellent thickness control. However, spin coating as a process has remained largely unchanged since it was first introduced in the 1960's, limiting its ability to produce the sophisticated components used in devices today. As modern technology evolves, a growing need for curved geometries has meant that complex manufacturing techniques have been adopted to meet the expanding requirements. It then poses the question, would the technology used today be designed in the same way if modern manufacturing processes were available? The ability to use accessible fabrication techniques when developing new products enables rapid prototyping of components, leading to the design of unique new devices. This research aims to present two mechanical systems that utilize rotation to provide simple, low-cost alternatives for the manufacture and characterization of curved thin film layers, thus enabling the continued progression of complex device design.

A review of current thin film coating and characterization methods was conducted to understand the applications and limitations of existing microfabrication techniques. Understanding the dynamics of a rotating fluid body was also critical to the conceptual development of a multi-axis spin coating machine. Enabling the design of a prototype rotational manipulator capable of controlling the shape and thickness of a coating by manipulating the evolution of the liquid through the induced rotational motion of a spherical substrate. The development of an optical analysis instrument is also discussed, detailing the design and manufacturing stages of the new experimental setup for coating and characterizing curved surfaces. These prototype systems were then trialled with various materials and geometries, including curved surfaces, to determine the capabilities of the proposed designs, informing future iterations of the machines. Implications for engineers and product designers were then reflected upon, where optimized coating and characterization systems are particularly relevant for the fabrication of curved components, which require conformal coatings with uniform thickness. Finally, the next stages of this research are outlined, highlighting the need for further modelling and prototyping stages to realize the goal of developing a cost-effective method for manufacturing devices on highly curved surfaces.

2 BACKGROUND

2.1 Review of thin film manufacturing

2.1.1 Coating techniques for thin films

Coatings have been used for centuries to decorate and protect various objects, with scientific developments expanding the functionality of coatings to be used in almost every active industry. The processes used to create these coatings have also evolved, with techniques such as dip-coating and flow-coating improving manufacturing efficiency and effectiveness (Cohen & Lightfoot, 2011). Currently, modern coating processes can be classified into several categories, including vapour deposition, electro deposition, spraying, and mechanical/contact methods (Pattankude & Balwan, 2019). These processes have specific applications and limitations, where the development of improved coating techniques continues to enable the design of new technology. Driven by the evolution of semi-conductor based industries, the need for progressively thinner coatings with a broader range of materials and functions is increasing (Franssila, 2010). These coatings, commonly referred to as thin films, have thicknesses on the micrometre or nanometre scale and are a foundation of microfabrication processes. Thin films are used in a wide range of devices, such as integrated circuits, magnetic data storage, microfluidic sensors, photovoltaics, and optics; where they form temporary or permanent surface structures, often adding functionality to a substrate (Abegunde et al., 2019).

Today there are many different techniques for manufacturing the thin films used within micro-devices, most of which are based on the previously described categories (Mbam et al., 2019). However, each method has benefits and drawbacks related to process complexity, coating and substrate materials, film thickness and uniformity, substrate topography, or detail resolution. One technique used in the manufacture of many common devices is spin coating, a process which involves coating a planar substrate with a thin uniform layer (Sahu et al., 2009). Spin coating uses centrifugal force generated through rotation about a central vertical axis to disperse a solvent-based liquid over the substrate surface. The solvent in the fluid layer then evaporates, solidifying into a thin uniform film. The process, as shown in Figure 1, can be divided into four key stages: deposition, spin-up, spin-off and evaporation (Scriven, 1988).

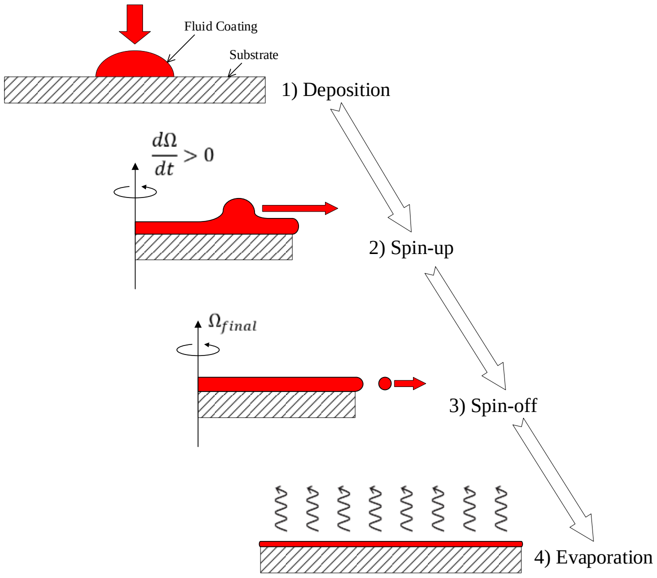

Figure 1. Stages of the conventional single-axis spin coating process with angular velocity Ω (Scriven, 1988).

Several studies have been conducted aiming to develop spin coating techniques that add new functionalities, however, these have been limited due to the fundamental balance between the viscous and inertial forces observed throughout the process. The addition of substrate curvature for example introduces uneven gravitational and surface tension forces, producing non-uniform and therefore, un-processable films. Single-axis spin coating has previously been used to coat slightly curved substrates in the optics industry such as in the study conducted by Reichle et al. (2008), and this concept was further expanded on by Jose (2020), who investigated the feasibility of single-axis spin coating on a hemispherical substrate. However, both studies found that the resulting films had a radial thickness distribution due to the curvature of the substrate.

2.1.2 Methods of film thickness measurement

Thin films are essential elements of many technological and scientific applications, where the ability to measure their thickness is critical for controlling coating processes and determining their functionality. Various thin film characterization techniques have been developed, with different methods utilizing specific physical properties of the thin film layer. Common measurement methods involve the inspection of a sharp edge (or step) or derive thickness from an interaction with the film at a continuous interface (King et al., 1972). Generally, surface characterization methods can be categorized by the type of interaction occurring, such as mechanical, thermal, electro-magnetic, acoustic, or optical (Harper, 2008). Each technique has its own advantages and drawbacks, such as being destructive, requiring physical contact, or needing complex sample preparation, expensive equipment or a highly controlled environment. Characterization methods also have unique limitations on measurement accuracy and efficiency, therefore it is typically the nature of the application that dictates which analysis technique is best suited (Piegari & Masetti, 1985).

Optical characterization techniques pose several key advantages when compared to other methods as they are commonly non-intrusive and quick responding, making them ideal for liquid coating applications. Optical systems utilize interactions at the thin film interfaces when excited by an incident electromagnetic radiation source (Perkowitz et al., 1994). Prevalent methods rely on a signal emitted from the excited film where phenomena such as fluorescence (Driscoll et al., 1992), absorbance (Barter & Lee, 1994), and reflection cause detectable spectral changes from which film thickness can be deduced. White light reflectance spectroscopy (WLRS) is a specific optical film characterization technology developed by ThetaMetrisis© that provides simultaneous thickness and refractive index measurements of thin film layers. Utilizing a broad-band (white) light source operating in a configurable range on the UV-Vis-NIR spectrum (350-1000 nm), WLRS improves upon previous reflectance techniques to characterize single or multiple thin film layers in the order of nanometres to millimetres (WLRS - ThetaMetrisis, 2019).

2.2 Rotating fluidic systems

2.2.1 Rotational dynamics

Rotating bodies are a core component of mechanical systems and thus, to describe the dynamics of mechanical systems, rotation in 3D must first be understood. Rotation of a rigid body causes inertial forces to be experienced by any mass connected to the body, including a fluid layer on a rotating substrate. These inertial forces, called centrifugal, Coriolis and Euler forces as described by equations (1-3), are products of the angular velocity $\boldsymbol{\Omega}$, position $\boldsymbol{R}$, and relative velocity $\boldsymbol{U}$, which are vectors defined in a rotating, body-fixed reference frame (Thornton & Marion, 2004). Figure 2 illustrates the body forces acting on a fluid layer on the surface of a 3D spherical body rotating about its centre, with an arbitrary angular velocity, described in spherical or Cartesian co-ordinates. Gravity is fixed to the global reference frame and therefore rotates relative to the substrate and connected fluid layer, as shown in equation (4), where the rotational transform $\boldsymbol{T_r}(t)$, denotes the time dependent rotational transformation matrix between the two reference frames.

$$\boldsymbol{F}_{centrifugal} = -m\boldsymbol{\Omega} \times (\boldsymbol{\Omega} \times \boldsymbol{R}) \tag{1}$$

$$\boldsymbol{F}_{coriolis} = -2m(\boldsymbol{\Omega} \times \boldsymbol{U}) \tag{2}$$

$$\boldsymbol{F}_{euler} = -m\frac{d\boldsymbol{\Omega}}{dt} \times \boldsymbol{R} \tag{3}$$

$$\boldsymbol{F}_{gravity} = -mg\boldsymbol{T_r}(t)\hat{\boldsymbol{k}} \tag{4}$$

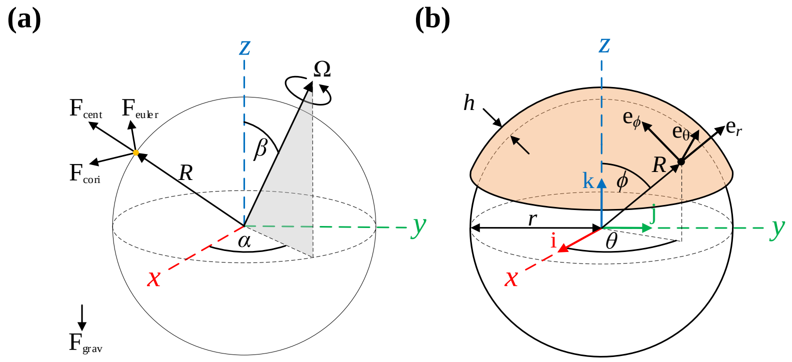

Figure 2. (a) System dynamics of a spherical body rotating about an arbitrary axis & (b) Geometry, and co-ordinate schemes for a liquid film on the exterior of a rotating sphere.

2.2.2 Fluid mechanics of spin coating

The governing physics of fluid dynamics can be derived through applying Newton's second law of motion to a flowing fluid body. The resulting equations are the Navier-Stokes equations which relate the rate of change in momentum to an applied force for any viscous, incompressible fluid (Fang, 2019), as described by equations (5-6).

$$\nabla \cdot \mathbf{u} = 0 \tag{5}$$

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u} = -\frac{1}{\rho}\nabla p + v\nabla^2\mathbf{u} + \mathbf{F} \tag{6}$$

Where $\mathbf{u}$ is the fluid velocity field at time t and p is the fluid pressure. ρ and v are fluid properties relating to density and kinematic viscosity respectively and $\mathbf{F}$ is the forcing term per unit mass combining all external forces acting on the fluid body. These governing equations ensures the conservation of mass and linear momentum respectively, and can be highly non-linear. In general, there exists no analytical solution for the Navier-Stokes equations, however models have been developed to predict the thickness of evolving thin film flows over rotating flat (Lee et al., 2019) and curved surfaces (Shepherd et al., 2022).

3 SYSTEM DEVELOPMENT

3.1 Multi-axis spin coater

3.1.1 Concept development

Previous investigations of spin coating over curved surfaces revealed that the uniformity of the fluid layer deteriorates when curved geometries are used in single-axis systems (Jose, 2020; Reichle et al., 2008). This is due to the uneven distribution of gravitational force across the surface along with the addition of potentially uneven surface tension forces. Therefore, for spin coating over curvature to succeed, 3D inertial forces must be generated through the addition of non-vertical rotation axes, enabling more degrees of freedom. Many multi-axis machines or manipulators exist, with various configurations and uses, ranging from basic rotors to complex robotic arms (Lewis et al., 2004). Several of which were explored for a new multi-axis spin coating system, with the internal, gyroscopic concept shown in Figure 3 chosen over an external manipulator resembling a robotic arm with a spherical wrist. Internal rotation has several advantages over an externally rotating machine as the substrate remains in a single point in space, simplifying the coating process, whilst the lower moment of inertia makes the system safer and easier to control. The substrate remaining in a single position further reduces the overall size of the machine, assisting with the deposition and clean-up processes, reducing the chance of defects.

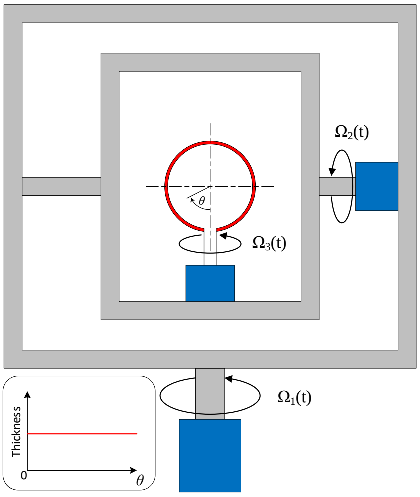

Figure 3. Initial concept for gyroscopic spin coating machine rotating a spherical substrate about multiple axis with individual angular velocities $\Omega(t)$.

Although having three intersecting axes of rotation would provide complete rotational freedom, the final prototype concept aimed for rotational speeds of 500-1200 rpm on two orthogonal axes to reduce the overall complexity of the machine. A custom spherical substrate was designed to be mounted in a balanced internal gimbal assembly which enabled rotation about both vertical and horizontal axes. The access to the substrate for deposition is through a central hole in the top shaft, with the lower shaft providing power to the gimbal, where the entire assembly was mounted inside an enclosure for safety with a transparent removable front cover to observe and change samples.

3.1.2 Prototype manufacture

The main body of the machine was constructed from 12 mm aluminium plate, creating a safe and stable enclosure for the inner gimbal assembly as shown in Figure 4. A 20 mm polycarbonate cover provides access to the inner gimbal, where a limit switch cuts power to the motors if the front cover is removed to avoid collisions with the rotating assembly. The CNC machined aluminium sample mounts directly onto the horizontal motor shaft, inside a balanced cage that is in turn driven by the larger vertical motor. Both motors have integrated hall effect rotary encoders to track motor states such as velocity to help control the dynamics of the spherical sample. Therefore, a slipring was used to transfer power and control signals to the rotating sample motor.

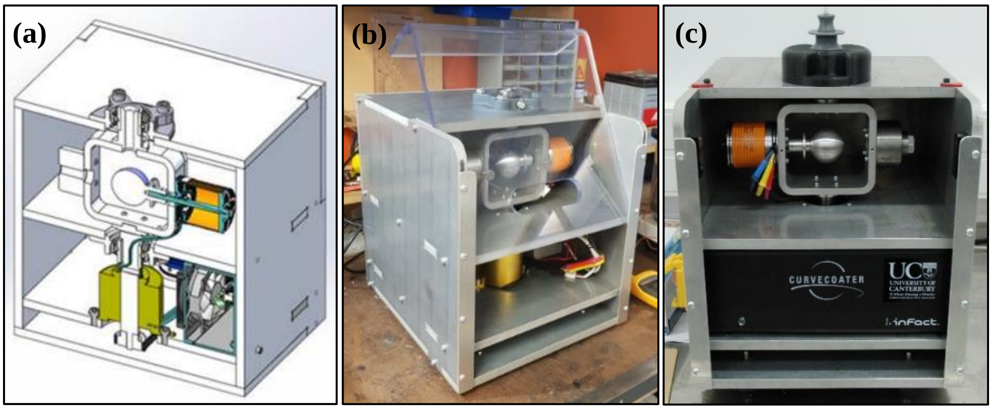

Figure 4. Development of prototype multi-axis spin coating system 'Curve Coater', (a) CAD model, (b) manufacture and testing, (c) lab setup.

3.1.3 Limitations of proposed design

Throughout the development of the multi-axis spin coating prototype, its effectiveness was repeatedly evaluated to improve the apparatus for both research and commercial applications. Several of the key sub-systems were consequently re-designed to improve the safety and functionality through the addition of numerous seals, guides and covers. However, the resulting machine also had some fundamental drawbacks with regards to its capabilities and operational process. Adding only one additional axis of rotation constrained the sample kinematics to specific orientations, and the secure enclosure prevented access to the substrate, which in turn was limited to particular sample geometries. These restrictions made it difficult to control the coating process by limiting management of the various phases of spin coating throughout operation. Although not critical to the development of the conceptual technique, the identification of these flaws suggested the need for further prototyping to improve the manufacturing method for commercial industries.

3.2 Curved surface characterisation

3.2.1 Design challenges

Besides film formation, the accurate characterization of films on curved surfaces also provided a challenge as most current techniques are designed to analyse planar thin film layers. Therefore, to successfully quantify experimental results, a new system had to be developed. Many of the reviewed film characterization methods were viable options, however each had unique limitations. The scale of the films thickness made traditional mechanical measurement impractical, whilst the physical contact required for thermal and ultrasonic thickness measurements damages the film and requires additional sensors to be integrated into the substrate. Hence, the most practical way to characterize films on the scale of micrometres was determined to be through optical techniques. A previously used method utilized a 3D scanning microscope to map the topology of the film’s surface in a small area (Jose, 2020). This optical profilometer (Filmetrics® Profilm3D) used white light interferometry (WLI) to map surface profiles, however, to calculate the thickness, the scanning area must contain a registration feature or ‘step’ to provide a datum at the substrate surface. This meant that the film had to be patterned, increasing the uncertainty of results due to the additional processing steps with no applicable way to control the patterning of a highly curved film. The curved substrate also required manual alignment and focusing for each measurement, making the characterization process cumbersome and imprecise.

3.2.2 Prototype overview

The final system design is shown in Figure 5 and aimed to utilize the versatility of the non-destructive WLRS method in the form of the FR-pOrtable probe (Thetametrisis©), created for in-situ point measurements of film layers. The probe head contains a broad-band variable wavelength light source with a corresponding spectrometer, both connected to the reflection probe via optical fibers. This reflection probe carefully directs the light out incident to the sample surface whilst also collecting the reflected light. The reflected signal is transferred to a PC-driven spectrometer where the processing software FR-Monitor is used to calculate thickness measurements of various coating types. The characterization system therefore consisted of a unique mounting unit for the measurement probe and sample. Attaching the probe to an adjustable rail on an arm that rotates around a horizontal axis enabled the tip to be positioned at the correct angle and distance from the sample's surface for accurate thickness measurements of highly curved films. A locking mechanism provides secure and effective indexing of the head angle, whilst a modular stage assembly is used to align the sample with the probe. To obtain a film's thickness profile, a series of measurements are taken around the sample surface at various head angles. Although this system was intended to be used with specific spherical samples, the modular capabilities of the adjustable components maximize the versatility of the design. Therefore, different configurations can be used to characterize a range of other sample geometries including cylindrical and ellipsoidal samples, or even concave surfaces.

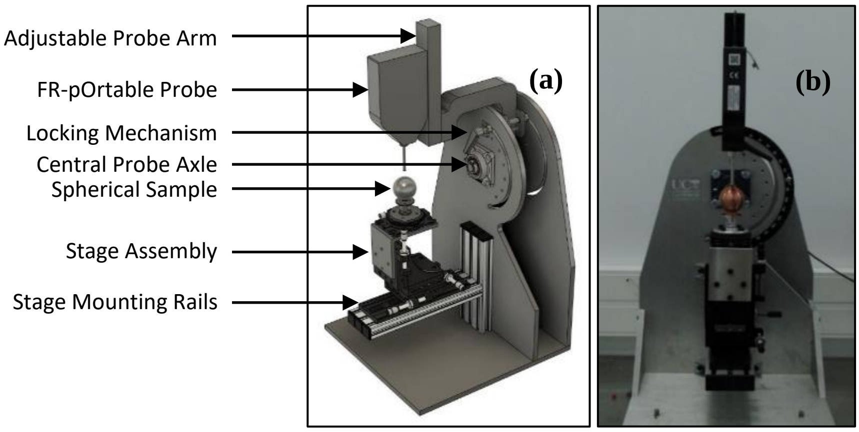

Figure 5. Curved surface WLRS characterization system showing key design features, (a) CAD model, (b) prototype machine.

4 EXPERIMENTAL METHODS

The new multi-axis spin coating system was verified through a series of single-axis tests comparing the process to existing spin coaters. This also provided an opportunity to observe how the substrate and fluid materials interact, with particular interest on how the substrate surface finish may affect the process. Tests were first conducted with surface ground 6061 aluminium (Al) flat disc substrates, enabling the comparison of results to a control coating of photoresist on a silicon (Si) wafer. Use of flat disks as substrates also enabled the verification of the new characterization system, by comparing measurements recorded with the WLRS method to those taken using WLI. Positive tone photoresist (AZ-1518, Microchemicals) was used to coat the 100 mm Si wafer and 70 mm Al disk substrates in a spin coater (PWM32-PS-R790, Headway) with a spin speed of 1000 rpm and acceleration of 2000 rpm/s for a duration of 60 s. Samples were then soft baked at 100 ˚C for 90 s before being exposed through a photomask using a 350 W mercury lamp (MA-6, Suss) for 25 s. The films were then submerged in developer (AZ-326-MIF, Microchemicals) for 60 s, after which a series of indexed thickness measurements were taken, ensuring that the WLRS signal was configured in a 600-900 nm bandwidth. This coating process was then repeated using the new multi-axis system, keeping the substrate horizontal whilst rotating about the vertical axis before using the WLRS method to make thickness measurements. Finally, the feasibility of curved surface device manufacture was investigated through a preliminary set of trials using the new coating and characterizing systems, where CNC machined spherical 50 mm Al samples were used to study the effects of various single and multi-axis motion schemes. Alternative positive tone photoresists (AZ-12XT, AZ-MIR-701, Microchemicals) were also used alongside AZ-1518 to investigate the impact of fluid viscosity when coating the curved substrates.

5 RESULTS & DISCUSSION

5.1 Spin coating on planar substrates

The thin film AZ-1518 coatings produced on the Al substrates throughout the vertical-axis trials (see Figure 6) using traditional spin coating machines were found to have average thickness of 5.0±0.2 µm or 4.4±0.3 µm depending on whether WLI or WLRS measurement techniques were used. These values were found to be considerably higher than the film thicknesses measured on the Si wafer of 4.6±0.2 µm and 4.0±0.1 µm using respective techniques to characterize a typical coating using the same process parameters. However, the thin film produced using the multi-axis spin coater had an average thickness of 4.2±0.1 µm, measured using WLRS, showing that the new system could accurately replicate the single-axis coating process. Several reasons outside of process variability may explain the discrepancies observed in these results, first of which could be the roughness of the Al substrates. The surface topography captures fluid creating a static layer that adheres to the Al samples, increasing the viscous shear forces experienced by the flowing fluid layer. Sample diameter and edge sharpness of the substrate can also influence the film thickness as the surface tension forces observed by the fluid coating changes due to the curvature of the bulge created before being dispelled in droplets. This can increase the pressure within the fluid layer collecting at the edge of the smaller substrates, thinning the region inside the edge whilst reducing the flow of fluid being expelled from the sample, increasing the overall thickness of the film layer.

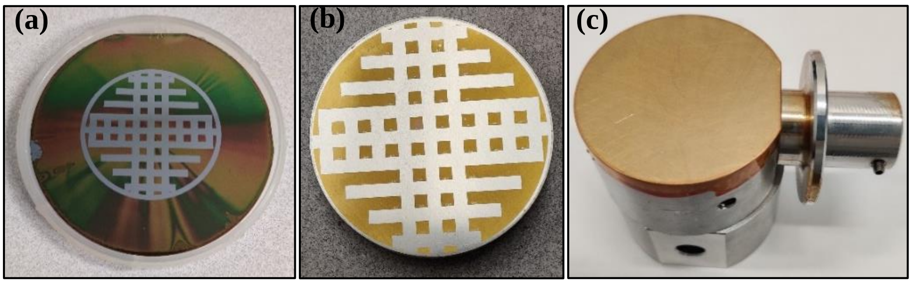

Figure 6. Thin film coatings produced from single-axis spin coating of AZ-1518 photoresist at 1000 rpm, (a) on a 100 mm Si wafer, (b) on a 70 mm Al disk, (c) on a 50 mm Al disk using the new multi-axis system.

5.2 Spin coating on spherical substrates

The multi-axis spin coating system was then used to produce thin curved film coatings on a spherical substrate. Results indicated that the thickness profile was directly dependent on fluid viscosity and substrate motion. Vertical axis spinning was the first logical test as this has been investigated previously by Jose (2020), when coating the outer surface of a sphere. The thickness profile of the thin film revealed a radial distribution, thinnest at the rotation axis pole whilst getting thicker towards the equator. Highly viscous fluids such as the AZ-12T photoresist resulted in much thicker coatings, however also required far more rotational energy to generate flows, often resulting in poor coating coverage and other defects such as the fingering shown in Figure 7(a). Dual-axis motion schemes were then implemented whereby the horizontal sample motor was used to vary the orientation of the substrate with respect to the dominant vertical axis of rotation, generating a dynamic inertial force that directed the fluid flow away from the point of deposition towards the Z-axis poles as seen in Figure 7(b-c). Finally, the processability of these thin curved film layers was investigated by using a flexible photomask to lithographically pattern a sample coated with AZ-1518, from which further etching processes could be used to create a 3D structure on these spherical surfaces. To assess coating distribution, the new WLRS characterization instrument was utilized to map the thin film layers, producing surface thickness profiles as shown in Figure 8. The resulting coatings had appropriate thicknesses for microfabrication applications (1-50 µm) depending on process parameters such as fluid viscosity and rotation speed. It was observed that regions with a highly uniform coating distribution could be formed by inducing complex substrate motion using dual-axis motion, suggesting that the manufacturing technique would be suitable for fabricating devices on highly curved surfaces.

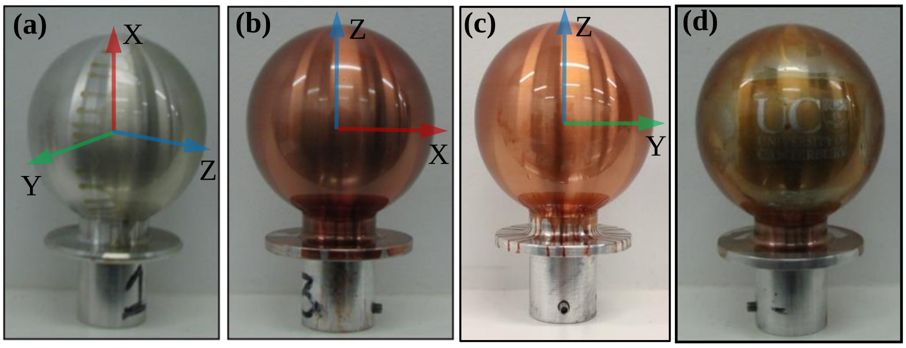

Figure 7. Curved thin film coatings formed on spherical 50 mm Al substrates using multi-axis spin coating system: (a) single-axis rotation using AZ-12T, (b) dual-axis rotation using AZ-MIR-701, (c) dual-axis rotation using AZ-1518, (d) patterned AZ-1518 sample.

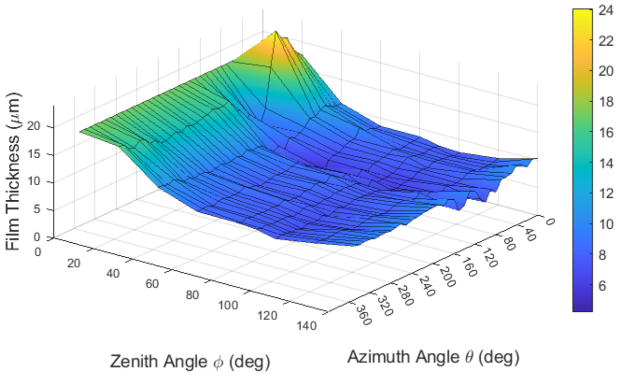

Figure 8. Thickness profile of AZ-1518 coating on 50 mm spherical substrate produced using dual-axis rotation of 560/1000 rpm for 60 s and measured using WLRS.

6 IMPLICATIONS FOR ENGINEERING DESIGN

Engineers and product designers involved in developing new devices are always constrained by the capabilities of the technology used throughout the prototyping and manufacturing phases of production. Historically, advances in coating processes such as spin coating have led to the foundation of many critical micro-device based industries and technologies (Franssila, 2010). However, modern microfabrication techniques are introducing new functionalities, including the ability to produce complex 3D structures on curved surfaces. Therefore, methods such as additive manufacturing are being increasingly utilized in product development and research applications (Rich et al., 2021; Wu et al., 2020). However, many of the systems capable of producing intricate components used in modern devices are expensive, have low output, and require a highly controlled environment, making them inaccessible or impractical. This research aims to continue the advancement of a versatile and widely used coating process by addressing a typical constraint on component geometry. An improved spin coating method would enable designers to consider the opportunities of complex and organic forms when developing new devices. This concept is particularly relevant in microfabrication industries where the tools outlined in this research may enable new possibilities in technical fields such as conformal electronics, optics, and the expanding array of microfluidics applications.

7 CONCLUSIONS & FUTURE WORK

Developments within the manufacturing industry are necessary to enable the continuous improvement of device designs used in modern technologies. Spin coating has been widely used to produce thin film layers critical to common micro-devices, however, it is typically limited to planar geometries. This research proposes improvements to the spin coating technique through the addition of one or more rotational axes, potentially enabling the manufacture of micro-devices with curved geometries by controlling the coating of a curved substrate. A prototype multi-axis spin coating system has been developed alongside a curved surface optical characterization instrument, which have been used to fabricate and quantify thin polymer films on the surface of a spherical substrate. Future works look to utilize corresponding fluid mechanics models to identify the optimal substrate motion kinematics needed to produce uniform thin film layers on a range of highly curved substrate geometries. Further system development is also needed to address the limitations of the current experimental setup, aiming to extend the functionality for commercial applications. Research outcomes will enable the manufacturing of micro-devices with highly curved geometries, which will open new possibilities in product design. The ability to fabricate micro-devices on curved surfaces eliminates the classic constraint on the geometric arrangement of device components. This will be a significant development for design and manufacturing industries, contributing to the continuous improvement of devices used in modern technologies.

REFERENCES

Abegunde, O. O., Akinlabi, E. T., Oladijo, O. P., Akinlabi, S., Ude, A. U., Abegunde, O. O., Akinlabi, E. T., Oladijo, O. P., Akinlabi, S., & Ude, A. U. (2019). Overview of thin film deposition techniques. AIMS Materials Science, 6(2), 174–199. https://doi.org/10.3934/matersci.2019.2.174

Barter, J. D., & Lee, P. H. Y. (1994). Real-time wave-amplitude spectrum analyzer for air-liquid interfaces. Applied Physics Letters, 64(15), 1896–1898. https://doi.org/10.1063/1.111761

Cohen, E., & Lightfoot, E. J. (2011). Coating Processes. In Kirk-Othmer Encyclopedia of Chemical Technology (pp. 1–68). Wiley. https://doi.org/10.1002/0471238961.1921182203150805.a01.pub3

Driscoll, D. I., Schmitt, R. L., & Stevenson, W. H. (1992). Thin Flowing Liquid Film Thickness Measurement by Laser Induced Fluorescence. Journal of Fluids Engineering, 114(1), 107–112. https://doi.org/10.1115/1.2909984

Fang, C. (2019). An Introduction to Fluid Mechanics. Springer International Publishing. https://doi.org/10.1007/978-3-319-91821-1

Franssila, S. (2010). Introduction to microfabrication. https://doi.org/10.1002/9781119990413

Harper, P. (2008). Measurement of film thickness in lubricated components using ultrasonic reflection. [PhD Thesis]. University of Sheffield.

Jose, B. (2020). Spin coating on curved surfaces. [University of Canterbury]. https://ir.canterbury.ac.nz/handle/10092/101336

King, R. J., Downs, M. J., Clapham, P. B., Raine, K. W., & Talim, S. P. (1972). A comparison of methods for accurate film thickness measurement. Journal of Physics E: Scientific Instruments, 5(5), 445–449. https://doi.org/10.1088/0022-3735/5/5/021

Lee, U. gi, Kim, W., Han, D. H., & Chung, H. S. (2019). A Modified Equation for Thickness of the Film Fabricated by Spin Coating. Symmetry. https://doi.org/10.3390/sym11091183

Lewis, F. L., Dawson, D. M., & Abdallah, C. T. (2004). Robot Manipulator Control: Theory and Practice, Second Edition.

Mbam, S. O., Nwonu, S. E., Orelaja, O. A., Nwigwe, U. S., & Gou, X.-F. (2019). Thin-film coating; historical evolution, conventional deposition technologies, stress-state micro/nano-level measurement/models and prospects projection: A critical review. Materials Research Express, 6(12), 122001. https://doi.org/10.1088/2053-1591/ab52cd

Pattankude, B. G., & Balwan, A. R. (2019). A Review on Coating Process. International Research Journal of Engineering and Technology, 06(3), 5.

Perkowitz, S., Seiler, D. G., & Duncan, W. M. (1994). Optical characterization in microelectronics manufacturing. Journal of Research of the National Institute of Standards and Technology, 99(5), 605. https://doi.org/10.6028/jres.099.058

Piegari, A., & Masetti, E. (1985). Thin film thickness measurement: A comparison of various techniques. Thin Solid Films, 124(3–4), 249–257.

Reichle, R., Yu, K., Pruss, C., & Osten, W. (2008). Spin-coating of photoresist on convex lens substrates. DGaO Proceedings.

Rich, S. I., Jiang, Z., Fukuda, K., & Someya, T. (2021). Well-rounded devices: The fabrication of electronics on curved surfaces – a review. Materials Horizons, 8(7), 1926–1958. https://doi.org/10.1039/D1MH00143D

Sahu, N., Parija, B., & Panigrahi, S. (2009). Fundamental understanding and modeling of spin coating process: A review. Indian Journal of Physics, 83(4), 493–502. https://doi.org/10.1007/s12648-009-0009-z

Scriven, L. E. (1988). Physics and Applications of DIP Coating and Spin Coating. MRS Proceedings, 121, 717. https://doi.org/10.1557/PROC-121-717

Shepherd, R., Sellier, M., & Boujo, E. (2022). Spin Coating on a Non-Axisymmetric Curved Substrate. University of Canterbury.

Thornton, S. T., & Marion, J. B. (2004). Classical Dynamics of Particles and Systems 5th edn (Belmont, CA: Brooks/Cole).

WLRS - ThetaMetrisis. (2019). https://www.thetametrisis.com/technology/wlrs

Wu, H., Tian, Y., Luo, H., Zhu, H., Duan, Y., & Huang, Y. (2020). Fabrication Techniques for Curved Electronics on Arbitrary Surfaces. Advanced Materials Technologies, 5(8), 2000093. https://doi.org/10.1002/admt.202000093