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ANNE NEVILLE

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Anne Neville spent much of her working life researching in tribology, surface engineering, and corrosion. These three areas are linked by the fundamental physics of surfaces. Anne was an engineer, and engineers build and design machines and devices with solid components. Yet, all these components have a surface—and that surface is often where the challenges arise. Anne had a passion for the physical understanding of what happens at a surface, whether it be corrosion, surface transformation either unintendedly, with corrosion, or with the deliberate engineering of the surface, or the study of surfaces in relative motion—tribology. Anne combined this passion for science with an ability to build teams and inspire co-workers, and a capacity for hard work to make tremendous achievements in these seemingly disparate fields.

Foreword

Every machine component or device has a surface. That surface is exposed to the atmosphere, and frequently the surface rubs against another. The bulk materials that make up components, metals, polymers, composites, are typically well defined. Not so surfaces. The physical and chemical interactions that happen at surfaces depend on a multitude of environmental and operational parameters. This is where Anne worked, at the surface. Her foundational studies on surface engineering, tribology, flow assurance, and corrosion helped us

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better understand what happens at the surface and so better design engineering components and machines.

Family and personal life

Anne grew up in Dumfries with her mother Doris (née Black), father Bill Neville, and older sister Linda. Her mother was a pharmacy technician, and her father a process lead at the ICI plant in Dumfries. She attended the Maxwellton High School and was a diligent student, giving up a promising badminton career to focus on her studies. Inspired by her maths teacher, a mechanical engineer by training, she chose to study mechanical engineering at Glasgow University when the prospectus fell open on the page with a Rolls-Royce gas turbine picture and she thought it looked interesting.

Anne met her husband Mark McKelvie at Glasgow University in 1988, where they were both studying engineering and lived in the same halls together. They married in 1999, and their daughter Rachel was born in 2005. Anne was a fantastic wife, mother, auntie, daughter and sister. Anne's love for her daughter Rachel knew no bounds and this was evident in everything she did. It did not matter how hectic Anne's research was getting, Anne would pick Rachel up from school on the vast majority of days and they would spend precious time together. Anne travelled all over the world on holiday with her family, but she was never more at home than when she was with Rachel and Mark on the beautiful beaches of Islay, Mull or Iona. Anne also loved visiting their holiday home in Tarbert on Loch Fyne.

Anne's success as an engineer is unquestionable but Anne also excelled as a human being. Her family and friends were always the most important aspect of her life. The comment that everyone who first met her would always make was that she was so 'down to earth' and had a natural ability to put people at ease. Anne also had a fantastic sense of humour, combined with a boundless compassion and care for others. Despite having an extremely large research group, she always inspired a sense of belonging. Organizing regular events both on campus and to the local countryside, be that Scotland whilst at Heriot Watt or the Yorkshire Dales when in Leeds. She ensured that colleagues' birthdays and significant family events within her research group were celebrated and personally helped those in need.

Anne Neville was a remarkable person in so many ways, but it is simply astonishing that she managed to continue living a normal life and achieve so much academically despite first being diagnosed with cancer in 2008 when her daughter was only two years old. Her resilience and determination to live life to the full were infectious and helped support those close to her. Anne decided to retire in November 2020 to spend her remaining time with her family and friends. Anne Neville died peacefully at home on 2 July 2022. As Anne had requested, her ashes were scattered at Kilnaughton Bay on Islay, where she had spent many happy times on holiday with her husband Mark and daughter Rachel.

Early career

She started her Mechanical Engineering degree at Glasgow in 1988. Anne's interest in corrosion began with a final-year project; and after graduating with First Class Honours, she continued her work in corrosion with a PhD at the University of Glasgow which was entitled 'An investigation of the corrosion behaviour of a range of materials in marine environments' supervised by Dr Trevor Hodgkiess. This sometimes involved several trips to the Marine Station on the island of Little Cumbria, where Anne's family joked that she was dangling pieces of stainless steel off the pier. Anne worked closely with colleagues at Weir Pumps and spent six months at the Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER) research laboratories near Brest, teaching herself French in the process.

Immediately after completing her PhD in 1995, Anne was appointed to a lectureship at Heriot-Watt University, where she began to apply for small research grants and build a research group. This team grew to 25 researchers in the following years, and in 1999 she was promoted to reader in addition to winning a prestigious Engineering and Physical Sciences Research Council (EPSRC) Advanced Fellowship. Anne was promoted to professor in 2002.

Whilst at Heriot Watt, Anne's interests broadened, and she joined a collaboration working on oilfield scale. Working alongside professors Ken Sorbie and Eric Mackay. Anne brought such a range of theoretical ideas and novel physical measurements to bear on this problem, that she made brilliant advances where previous progress had been rather slow. This was a collaboration that brought Anne much satisfaction and she continued to co-lead after her move to Leeds.

The Institute of Functional Surfaces, University of Leeds

In 2003, Anne moved her team of 20 researchers to the University of Leeds, initially to form the Institute of Engineering Thermofluids, Surfaces and Interfaces, which, with further growth in corrosion, tribology and surface engineering research, led to the later establishment of the Institute of Functional Surfaces (IFS).

IFS was to become a leading UK centre of excellence on functional surfaces, growing to 70 researchers at the time of nne's retirement, with a funding portfolio spanning many agencies and industrial sectors, including medical, oil and gas, and automotive. Some of the achievements of the IFS include: the first *in situ* synchrotron study of corrosion products growth, development of bespoke equipment for *in situ* study of tribo-chemistry processes underpinning unique mechanistic and multiscale numerical models, the first demonstration of the role of mixed-metal coupling on tribo-corrosion at the femoral stem–cement interface, the first 3D nano-printing system using tribo-reactive materials, and a coating strategy for flexible substrates to boost the hydrogen evolution reaction performance.

Anne was instrumental in setting up long-lasting partnerships with universities including Sheffield, Heriot Watt, Ljubljana, Lulea, Chengdu, Wuhan and Harbin. Partnerships with industry included Infineum, Croda (now Cargill), Total, Parker Hannifin, ExxonMobil, Lubrizol, Equinor, DePuy and Afton Chemical.

Engineering and scientific contributions

The thread that ran through Anne's impressive range of research activities was the understanding and design of functional surfaces. Anne was aware that solutions to these challenges lay in a detailed understanding of aspects of engineering science.

She worked broadly in two main fields: the first being corrosion and flow assurance, and the second being tribology and lubrication. The sciences that supported these two engineering areas were tribo-corrosion, electrochemistry, nano-science, surface science, and multiscale modelling.

The underpinning nature of these sciences meant that her research work was applicable in many industrial and medical sectors. Anne made contributions in several of these fields, which are described below across five interlinked themes: mineral science and flow assurance, oilfield corrosion and tribo-corrosion, bio-tribo-corrosion, tribo-chemistry, and friction.

Mineral scaling and flow assurance

The formation of scale in oil production systems presents a technical challenge. For example, the spring cavities and inner walls of the sub-surface safety valve can accumulate deposits of precipitated scale that impede the smooth operation of the valve and pose serious regulatory and safety risks such as the malfunctioning during well blow-out.

Anne carried out a large body of research on mineral scale formation and deposition on surfaces. Most of this work was through long-term involvement with colleagues in the Flow Assurance and Scale Team (FAST) at the University of Leeds and Heriot Watt, including Ken Sorbie, Eric Mackay, Frederick Pessu and Thibaut Charpentier, with sponsorship from up to 22 industrial companies.

In the area of mineral scale deposition, the central problem was on the formation of calcium carbonate ($CaCO_3$), barium sulfate ($BaSO_4$) and a few other mineral scales. Calcium carbonate usually deposits owing to the changing temperature and pressure of the produced brines in an oil well. Barium sulfate, however, is usually formed by the mixing of injected brines (seawater) rich in sulfate ions (*ca* 2700 mg l^{-1}) mixing with *in situ* reservoir brines that are often rich in barium ions (from *ca* 50 to *ca* 2000 mg l^{-1}). However, in most early research on scale formation of both calcium carbonate and barium sulfate, the focus was on the bulk solution chemistry and thermodynamics of the scale formation through familiar growth concepts, such as nucleation and crystal growth processes. The role of the supersaturation of the brine for the specific mineral of interest was seen to be the key feature governing mineral deposition. Whereas this is not wrong, it is certainly not the whole story. Anne's work highlighted the critical role played by the surface itself where the mineral was forming. An excellent review of the mineral scale research at Leeds was written by Anne herself (19)*. Those who knew Anne well hear her voice when reading this review. Her specific contributions to the study of mineral deposition can be summarized under the following four headings.

* Numbers in this form refer to the bibliography at the end of the text.

Understanding mineral scale formation mechanisms on surfaces

Anne Neville's research led to several very valuable insights on the mechanisms of scale formation and subsequent growth of mineral crystals on surfaces. She studied many of the factors that influence crystal morphology and composition, alongside the influence of surface properties such as surface energy, roughness and surface chemistry. This understanding has played an important role in the development of effective strategies to control mineral scale deposition in the oil and gas industry. Anne and her co-authors (3, 21) investigated the effect of the interaction of calcium carbonate supersaturation ratio with metal and polymer surfaces on the size morphology of calcium carbonate crystals and their growth on the surfaces. The work demonstrates the differences from $CaCO_3$ crystals formed in bulk precipitation.

A striking early finding in Anne's research (1) was about the effects of 'sub-MIC' scale inhibitor. The MIC (minimum inhibitor concentration) of a scale inhibitor (SI) is the notional concentration at which it effectively prevents or greatly reduces the scale deposition from solution. Typically, MIC values range from *ca* 1 mg l^{-1} for quite mild scaling problems up to *ca* 100 mg l^{-1} for more severe cases. A typical range in the oilfield is around MIC *ca* 3–10 mg l^{-1} (ppm for brines). Conventional thought was that if the target concentration fell to below the MIC value, then the SI would still give at least some level of protection against mineral deposition. Anne postulated that this was not the case and that dropping below MIC could make the deposition of barium sulfate *worse* than having no SI present at all. With co-workers she designed a series of experiments to test this rather strange effect, and, of course, Anne was right. As the SI concentration falls below MIC, the formation of barium sulfate scale on the surface actually increases, and the reason for this is explained in the paper (1).

New surface engineering techniques

It became obvious to Anne that understanding the role of the surface led directly to trying to engineer the surface to control unwanted mineral scale deposition. Much of the ensuing research was funded by industry (TotalEnergies, ConocoPhillips and Equinor) and these surface engineering strategies are now used for the management of scale deposition, particularly in valve components.

Anne and her collaborators (14) studied, developed and tested a wide range of surface engineering techniques to mitigate mineral scale deposition on oilfield surfaces. These techniques include surface modification, surface treatments and coatings. Anne showed that the application of appropriate surface engineering techniques could significantly reduce mineral scale formation both in the laboratory and in field tests.

Several classes of surface were studied, including bare and treated metal, various polymers, and diamond-like carbon (DLC). A systematic ranking of the surface resistance to scaling was established along with an improved description of the scale deposition process. Anne produced many papers in this area and made several important specific advances in our understanding of the interaction of the surface with the depositional process.

Advanced analytical techniques for mineral scale analysis

Anne (2, 13) pioneered the use of a wide range of analytical techniques to study mineral scale formation at surfaces. These included scanning electron microscopy (SEM) (and environmental SEM, ESEM), X-ray diffraction (XRD) and atomic force microscopy (AFM) to study mineral scaling process and the crystal structure and morphology of deposits such as calcium carbonate and barium sulfate scales, providing new insights into the surface growth mechanisms that were operating.

Anne (15) introduced the use of real-time synchrotron XRD (SXRD). She applied this to various systems, including the deposition of barium sulfate on surfaces. Her brilliant idea was to 'observe' in a synchrotron beam line (a highly intense X-ray source) the kinetic process of barium sulfate surface deposition. This insight allowed the imaging of various crystal planes of barite (011, 111, 201 etc.) growing kinetically. As a scale inhibitor was introduced, it was possible to observe which planes were inhibited and which planes actually grew faster. The net effect was ultimately that the highly distorted crystals were meta-stable and easier to inhibit and manage.

Improving the durability and lifespan of oilfield equipment

Mineral scale deposition can cause significant damage to oilfield equipment, leading to costly repairs and downtime. Anne's research has contributed to the development of more durable and corrosion-resistant materials for oil and gas infrastructure, as well as strategies to extend the lifespan of existing equipment. Examples of this are referred to in her review (19) and the practical papers describing field testing of the various techniques developed by her group.

Oilfield corrosion and tribo-corrosion

Anne developed an interest in oil and gas corrosion very early in her career. Continuing in the same vein as her PhD thesis, she translated her knowledge of erosion–corrosion processes in the marine industry to tackle material degradation challenges associated with hydrocarbon production.

Erosion–corrosion in oilfield applications

Anne's early work revolved around the assessment of erosion–corrosion in CO_2-saturated brines laden with sand particulates. At Heriot Watt, Anne initiated activities with Baker Petrolite (as Baker Hughes were known at the time) to study the action of surfactant-based corrosion inhibitors and their potential to mitigate the effects of erosion–corrosion (4). This work paved the way for several follow-on studies which revealed important observations in relation to the ability of inhibitors to mitigate components of erosion, as well as those attributed to electrochemical dissolution of carbon steel (9, 10)

After moving to the University of Leeds, Anne established an erosion–corrosion laboratory, consisting of electrochemical cells and a 'fleet' of submerged impinging jets and rotating cylinder electrodes. This catalysed her research activities in oil and gas, and her work broadened to encompass multi-phase flow systems (16), as well as erosion–corrosion of protective corrosion products (17).

An early, notable contribution from Anne's research arose from a collaboration with Shell UK. This work sought to understand and define chemical mitigation techniques to suppress high corrosion rates on an offshore oil and gas facility (18). Techniques were developed to understand and quantify the performance of corrosion inhibitors for field applications, particularly in the context of erosion–corrosion (22) and preferential weld corrosion (23). As a result of this work, Anne recommended the chemical treatments that should be applied to the facility to maintain degradation rates at acceptable levels.

Anne's research interests then encompassed erosion–corrosion of corrosion-resistant alloys (24), where *in situ* electrochemical measurements were used to study de-passivation and re-passivation due to sand impacts. Here, Anne highlighted the importance of electro-chemical–mechanical interactions, identifying a critical solid particle energy or de-passivation of alloys by following current transients in erosion–corrosion after solid impact. This work was complemented with acoustic emission measurements to aid in decoupling mechanical wear and electrochemical dissolution *in situ* (25).

Hydrogen sulfide corrosion

By 2012, Anne's corrosion activities were well established, particularly as she had transitioned her group into a new, fully refurbished lab in the heart of Mechanical Engineering at Leeds. This new home for corrosion research triggered Anne's latest research interest: hydrogen sulfide (H_2S) corrosion. Supported by a team of dedicated researchers and technicians, Anne established a bespoke H_2S laboratory. At the time, the laboratory was one of a kind, with the use of H_2S gas being exceptionally rare in UK academic institutions. Her publications examined the complex interplay between general and localized corrosion of active materials, whilst also understanding the associated synergy with temperature, chloride content, and acid gas partial pressure (37).

In situ measurement of corrosion mechanisms

A recurrent interest of Anne's was the development of unique test cells facilitating *in situ* and real-time measurement. Principal amongst these was *in situ* synchrotron flow (figure 1), which, for the first time, was able to follow the simultaneous evolution of corrosion and corrosion product formation in a hydrodynamic CO_2 corrosion environment, *in situ* and in real time (32). This work shed new light on the process of iron carbonate precipitation and its relationship with localized corrosion/pitting, a mechanism in which Anne became increasingly interested (42). Much of the latter stages of her career focused on generating a deeper understanding of this particular corrosion product (45), as well as continuing her research in erosion–corrosion (43), and exploring corrosion in acidizing processes (49).

Corrosion in carbon capture and storage

Towards the latter stages of her career, Anne took a keen interest in carbon abatement and the concept of carbon capture and storage (CCS) (38). She recognized that there were two key scientific questions in relation to dense phase (supercritical) CO_2 transport that must

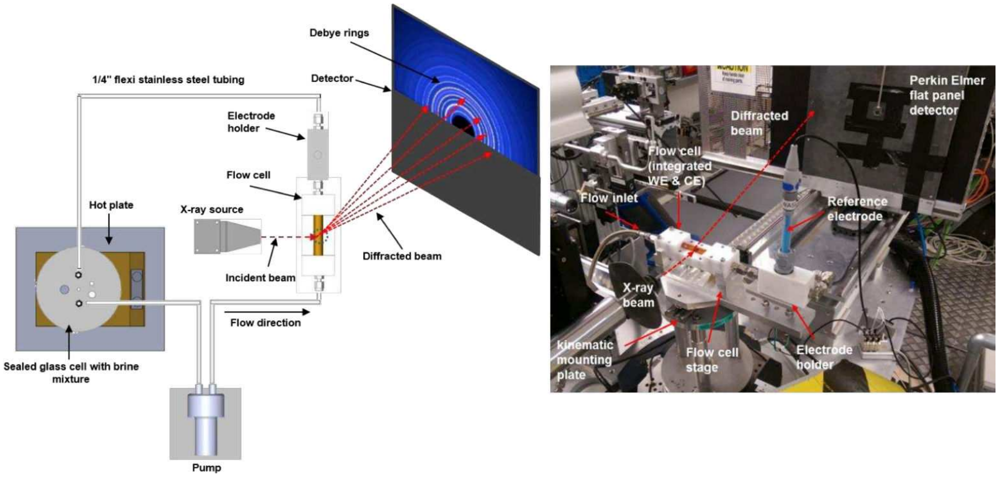

Figure 1. Photograph (*right*) and schematic (*left*) of the *in situ* synchrotron electrochemical flow cell set-up used on the Diamond Light Source beamline. (From (32), with permission from AIP Publishing.) WE – working electrode and CE – counter electrode.

be addressed before progress can be made in making CCS a viable and economic means of reducing carbon emissions. One related to the level of water and other impurities that can be tolerated such that corrosion of the pipeline network is manageable, and the other was regarding the prediction of *localized* versus *general* rates of corrosion.

Through a fusion of gravimetric, electrochemical and surface analysis measurements Anne was able to demonstrate how 'safe' limits of impurities can been defined through generation of pitting versus general corrosion analysis, and the construction of maps (44).

The role of water (30) and sulfur dioxide (SO_2) (31) as a contaminant in under-saturated and saturated supercritical CO_2 was explored as well as comparisons of different alloy pipeline materials (39).

Bio-tribo-corrosion

Corrosion is also an important degradation mechanism for prosthetic devices in the human body. However, corrosion was largely ignored as a degradation mechanism in hip joints from the initial design of hip-joint simulators in the late 1960s until 2003 when Anne's work in this field began. Anne introduced the principles of tribo-corrosion and tribo-chemistry into the joint-replacement durability domain. A new field of bio-tribo-corrosion, uniting the concepts of corrosion and lubrication, was established with the close collaboration of Professor Duncan Dowson FRS.

Figure 2. Anne in front of the physical vapour deposition (PVD) coating machine (copyright of the University of Leeds).

Mechanisms of bio-tribo-corrosion and tribo-film formation

Early studies in this area (5) were based on simplified pin-on-plate configurations to demonstrate the importance that lubricant properties play on the total degradation rate—the 'lubricant' in this instance being fluids with a range of proteins and amino acid species. The level of wear–corrosion interactions of CoCrMo alloy and stainless steel depended strongly on the fluid composition, with corrosion accounting for up to 50% of the total material lost.

Anne's group used advanced surface measurement techniques to elucidate the mechanisms of tribo-film formation in hip joints. Through X-ray photoelectron spectroscopy (XPS) and focused ion beam SEM (FIB-SEM) (6), it was demonstrated that organo-metallic protein complex films of thicknesses 15–80 nm were found on the surfaces, which grew and developed with the metal oxides (Cr_2O_3/CoO, etc.) as sliding progressed, and were linked to decreased total material loss. The application of transmission electron microscopy (TEM) and electron energy loss spectroscopy (EELS) (29) would later show the formation of amorphous carbon, graphitized layers that protected the contact, and crystallites of cobalt sulfide (Co_3S_4) were seen to emerge from tribo-chemical transformation of proteins in the contact.

Further studies (7) went on to demonstrate that the tribo-electrochemical degradation mechanisms were affected by surface voltage, environment, material couples, and tribological condition. As part of these studies, wear-induced passivation was reported for the first time; near-zero charge transfer through formation of proteinaceous tribofilms was hypothesized as the principal mechanism.

Later studies (20) turned towards understanding degradation processes of metal-on-polymer systems—more commonly found in total hip replacements. Again, the chemical aspects had received little attention and Anne's work undoubtedly demonstrated their importance. Complex interactions between materials tribology, corrosion, and lubricant chemistry were observed, including polymer transfer films and non-typical transient CoCrMo wear behaviour. Anne was at the forefront of providing computational models (46) which for the first time coupled mechanical and chemical processes in a way that enabled wear–corrosion synergies and mass loss to be accurately predicted.

Tribo-corrosion in hip simulators

In 2009, the first hip-simulator study with a three-electrode electrochemical cell was published (11). Prior to this, artificial joint performance was based on gravimetric results—assessing only mass loss during the running period. Her work was the first to electrochemically instrument a pendulum friction hip simulator and this has given a unique insight into the levels of corrosion occurring in metal-on-metal implants. This work provided direct evidence of tribo-chemical processes within clinically representative components and showed a direct link between lubrication and corrosion.

Subsequent studies (12) identified that particles, commonly generated during surgery or through implant wear, adversely affect implant passivity and increase corrosive degradation. The subject of metal-on-metal hip replacements and their failure mechanisms was to receive widespread publicity in 2010 after a high-profile medical recall by the manufacturer.

A comprehensive model that links the corrosive degradation of a metal sliding contact to total wear had long been one of Anne's goals (26). Initial attempts to correlate repeating patterns noted in anodic currents measured from metal-on-metal bearings were made with a so-called 'severity factor':

$$I \propto \frac{W\omega}{h_{\min}},$$

where I is the current generated by sliding (A), W is the axial load (N), ω is the angular velocity (rad s^{-1}) and $h_{\min}$ is the theoretical minimum film thickness (nm).

The 'severity factor' demonstrated a similar-shaped profile to anodic current transients. The peaks did not appear to align, however, and the onset of current was often in advance of high-severity portions of the cycle—a surprise, since current would be expected to follow surface damage.

With funding from the major EU FP7 LifeLongJoints project, Anne's group were able to build 6DOF (six degrees of freedom) unique electromechanical joint simulators that could replicate natural human biomechanics with a much higher degree of control. They investigated (33) the role of patient factors, such as gait profile, on the degradation of metal hip bearings. They demonstrated that adverse loading conditions may change material loss due to wear and corrosion by an order magnitude. With this improved control it was possible to link corrosive degradation to the tribological conditions at a given point in a cycle with peaks in current, and thus de-passivation occurs at the same point in the cycle despite cycle frequency (40).

Anne's domain of research was not only limited to academic studies, but also extended to emerging clinical challenges. In 2007, working with surgeons based at Norfolk and Norwich University Hospital and with DePuy International, tribo-corrosion concepts were applied to non-traditional tribological interfaces to explain higher-than-expected revision rates of the Ultima TPS metal-on-metal hip replacement. The work (27) demonstrated that micro-motion at the stem–cement interface resulted in high corrosion rates. The role of bone cement (previously presumed inert) in the crevice corrosion resistance of CoCrMo and 316L stainless steel was also demonstrated (28).

Anne demonstrated that considering the implant as a system was vital to understand the scientific process *in vitro*. Her findings that 50% of damage in hip joints can be attributed to corrosion changed the landscape within which hip joints are developed. Her work on medical device tribo-corrosion contributed to understanding the underlying degradation mechanisms and the nature of the tribo-film that formed as an interaction between rubbing surfaces and the complex biological lubricating fluid. Her work impacted on the development of new design rules, and removal of potentially toxic implants, and contributed to policy for device testing and regulation. The ultimate impact lies with the patient, who now enjoys a better quality of life through more durable implants.

It was primarily for this work and her work on tribo-chemistry (described in the next section), 'revealing diverse physical and chemical processes at interacting interfaces, emphasising significant synergy between tribology and corrosion', that Anne received the 2016 Royal Society Leverhulme Medal.

Tribo-chemistry

In the domain of tribology, Anne's research was focused on phenomena in boundary and mixed lubrication where the oil film between rubbing surfaces is insufficient to prevent solid contact. The performance of contacts in these regimens is controlled by the formation, removal and replenishment of nanometre-thick reactive films, called tribo-films. To advance the understanding of tribo-films required a combined approach of advanced surface analytical techniques, such as SEM/energy dispersive X-ray (EDX), XPS, X-ray absorption near edge structure (XANES), focused ion beam transmission electron microscopy (FIB-TEM), secondary ion mass spectrometry (SIMS), nanoindentation, Raman spectroscopy, and AFM.

These phenomena are particularly relevant to automotive lubrication, where lubricants contain anti-wear additives to promote tribo-film formation. Anne studied two additives in particular: zinc dithiophosphate (ZDDP) and molybdenum dithiocarbamate (MoDTC). Her work (8) described the formation rate of films as the sum of chemisorption, physisorption and removal, and led to new methodologies for quantifying formation kinetics.

Atomic force microscopy (AFM) was used as part of these studies (51), first to generate tribofilms using repeated passes of the AFM tip, and second to probe their apparent viscosity by measuring the creep of the film material under a static probe loading. Anne's team demonstrated that the films behave in a similar manner to a molten glass with an average viscosity of 10^{12} Pa s.

These experimental observations were used as the basis for developing a numerical thermodynamics model (34) of the interface coupled with a contact mechanics solver to predict the rate of film formation and wear.

Anne's analytical and experimental research extended to study also the tribo-chemistry processes on non-ferrous surfaces such as diamond-like carbon (DLC) coatings, which were being used increasingly on automotive engine parts (figure 2). One key finding was analysis of compatibility issues, especially the explanation of excessive hydrogenated DLC coating wear when lubricated with an MoDTC-containing lubricant (35).

This research led to the development of new lubricant additive solutions as well as optimized surface engineering recipes (36) that improve friction and wear performance through a coating/lubricant synergy.

In an unusual application of interface tribo-chemistry, Anne exploited the processes to develop a novel 3D nanoprinting technique (47), where repeated passes of an AFM tip were used to create tracks on a surface (see figure 3). This novel nanomanufacturing methodology opened future possibilities to utilize the nanoprinted films for the expanding fields of microelectronics, medical devices, flexible electronics, and sensor technologies.

Anne's research in this field provided the experimental evidence of tribo-reaction pathways between engine oil additives and surfaces. She demonstrated how tribo-films were formed and their role on friction and wear reduction. Much of this work was done in collaboration with engine lubricant and lubricant additive manufacturers, and is now used to develop and optimize low-friction lubricants for automotive industries.

Friction—new tools and techniques

Friction was a topic close to Anne's heart; she referred to it as the 'Tribology Enigma'. In 2016 Anne gathered her thoughts on this subject and assembled a team of experts to make some tangible progress in this area. Anne identified the futility of searching for a universal law of friction, but instead approached the problem by identifying the key areas in science where friction played an important role and using these as test beds to build a new, deeper understanding of the processes. These concepts were embodied in an EPSRC Programme Grant between the universities of Sheffield and Leeds that ran from 2017 to 2023.

Much of Anne's work in this programme was to develop new tools and techniques for the study of friction. She designed and built new test platforms to study the micro-scale motions that occur in tribological phenomena. One such device (41) was built to fit inside the synchrotron beam line to use X-ray absorption spectroscopy (XAS) to investigate tribo-film formation occurring *in situ* in rubbing contacts. Using this device it was possible to study the chemical processes of film formation in tandem with the changes in frictional behaviour.

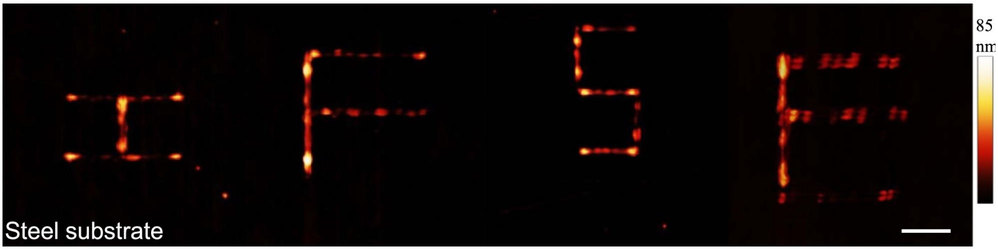

Figure 3. Atomic force microscopy images of 3D tribo-nanoprinted track of Anne's research group initials (scale bar, 2 μm) (provided by Ardian Morina).

Another test platform was built to study the micro-motions that occur in fretting contacts, such as the femoral head–stem interface. Using multi-axis micromotion sensors, it was possible to track the small oscillations leading to stick-slip motion fretting loops, wear, and crack initiation.

Friction between particles is a key parameter in the flow of granular materials in, for example, the pharmaceutical industry. Solid lubricants, known as glidants, are often used to modify inter-particle friction to improve powder characteristics such as flowability and compactability. As part of this programme, Anne and co-workers studied many aspects of the inter-particle friction process. Surface analysis techniques were used to study how glidants dispersed on a particle surface, and tribometers to quantify the effect on adhesion and friction (48). These data were used to build better boundary conditions for discrete element modelling (DEM) of granular flow (50).

An emerging area for Anne was the study of the mechanisms of charge generation in tribological contacts (52). The purpose here was to define the underpinning science behind tribo-electric nanogenerators (TENGs). A tribometer was modified with a high-impedance electronic circuit to study the build-up of electric charge and the induced current during a rubbing contact. This was used to quantify the effect of surface topography, friction, and shear stress on charge transfer and how wear and the build-up of transfer films broke down accumulated charge.

The health of the discipline

Anne was a leading figure in the tribology and corrosion research communities. For many years she chaired the organizing committee of the Leeds–Lyon Symposia on Tribology, an important annual event in the tribology calendar, and was guest editor of the Symposium special issues.

She was on the editorial boards of several journals, including *Anti Corrosion Methods and Materials*, *Wear* and *Surface Engineering*. In 2006, she established a new journal, *Tribology—Materials, Surfaces & Interfaces*, published on behalf of the Institute of Materials, Minerals and Mining. Her aim was to provide a platform for the increasing use of surface analytical tools in tribology, which resulted in a deeper understanding of tribo-chemical, tribo-physical and tribo-corrosion reactions.

Anne played a leading role in training the next generation of research scientists and engineers. At the heart of her research team were her PhD students; in total Anne supervised 129 PhD candidates to graduation. Her approach was one of empowerment, and she made each one feel valued and special. Anne was a co-developer of the Erasmus Mundus Masters' programme 'European Master in Tribology of Surfaces and Interfaces' (2014–present) in partnership with the universities of Lulea, Coimbra and Ljubljana. This partnership then led to the development of a doctoral innovative training network and to a postdoctoral-level project, training more than a hundred masters, doctoral and postdoctoral tribologists.

In 2013 Anne, jointly with colleagues at the University of Sheffield, created the EPSRC Centre for Doctoral Training in Integrated Tribology. The 'Integrated' in the title referred to the integration of the subject across length scales, industry sectors, engineering disciplines, and technology readiness levels. The centre trained 55 PhD students during the period 2014 to 2023 with sponsorship from 33 industrial companies. The groups of students were jointly registered at both Leeds and Sheffield and benefited from access to laboratories and academic expertise at both sites.

Anne

Anne was a force of nature, hugely energetic, productive and focused. The sheer volume of her output is a testament to her energy and dedication. Anne's contributions to her chosen discipline and her professional achievements are many. She was a great leader, and could bring people together and inspire them to achieve their very best. Whilst Anne had much to brag about, she never did; she was the rarest of professors—one without an ego. She was an outstanding female role-model and combined a successful career with a full family life. Anne was brilliant, selfless, thoughtful and kind. She will be greatly missed.

Professional distinctions

1999	84th Makdougall Brisbane Prize from the Royal Society of Edinburgh
2005	Elected Fellow of the Royal Society of Edinburgh
	Elected Fellow of the Royal Society for Arts, Manufactures and Commerce
2007	Elected Fellow of the Institution of Mechanical Engineers
2008	Inaugural Royal Academy of Engineering Chair in Emerging Technologies
2009	Elected Fellow of the Institute of Materials, Minerals and Mining
2010	Elected Fellow of the Royal Academy of Engineering
2011	Institution of Mechanical Engineering, Donald Julius Groen Prize for Achievements in Tribology
2013	Royal Society Wolfson Research Merit Award
2015	Medical Research Council Suffrage Science heirloom recipient
2016	Royal Society Leverhulme Medal
	IMechE James Clayton Prize

	Officer of the Order of the British Empire, New Year Honours List
2017	Elected Fellow of the Royal Society
	Honorary Doctorate from Heriot Watt University
	Advanced European Research Council Fellowship
2019	Honorary Doctorate from the University of Glasgow
2021	Royal Society Clifford Patterson Medal

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The frontispiece portrait photograph was provided to the Royal Society by the subject; copyright unknown.

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Rob S. Dwyer-Joyce, FREng is a professor of Lubrication Engineering and Tribology in the Department of Mechanical Engineering, University of Sheffield, where he leads the Leonardo Centre for Tribology. Rob had the honour of working closely with Anne as co-directors of the EPSRC Centre for Doctoral Training in Tribology and the EPSRC Programme Grant Friction: the Tribology Enigma.

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