National Physical Laboratory

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ROLE OF METROLOGY IN THE DIGITALISATION OF SURFACE ENGINEERING

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Role of Metrology in the Digitalisation of Surface Engineering

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Approved on behalf of NPLML by
Stefanos Giannis, Science Area Leader AEM Group

Contents

1 EXECUTIVE SUMMARY

Industry 4.0 offers an opportunity to connect, improve and accelerate the development of new products, and to optimise their life cycles and supply chain dependencies. The essence of Industry 4.0 is digitally enabled design, production, and optimisation of supply chains. Data is at the heart of all this and appropriate measurements generate the trust and assurance in that data so that it can be used to develop the models and digital twins that can be used to predict in service performance and accelerate product design. Measurements are also essential to enable the correct control of processing conditions and parameters to ensure high quality products are produced.

Surface engineering offers a range of technologies that can be used to improve the characteristics of surfaces leading to benefits beyond improved functional performance, such as contributing to the targets of net zero carbon emissions and increased sustainable use of materials. The Surface Engineering Leadership Forum (SELF) in its strategy [2] has identified digitalisation as a key step in the transformation of the surface engineering industry by 2025 leading to the creation of growth in sales from £11bn to £25bn by 2025 with the creation of an additional 50,000 jobs.

To gain more detailed information on the role of metrology in surface engineering, a consultation exercise was carried out with industry and other stakeholders, supported by SELF and the EPSRC Networkplus on Digitalised Surface Manufacture.

Eight representatives from surface engineering firms were interviewed and a workshop held with 24 stakeholders to get their views on key questions including:

- What properties do we most need assured data for?
- Which sectors need to be addressed?
- What are the specific applications within these sectors?
- How do we plan to use the data captured?
- What models and algorithms do we need to develop and implement?
- What do predictive twins look like?

With respect to the properties of engineered surfaces, the highest interest was shown in tribological performance such as wear and friction and adhesion of coatings. The measurement of coating thickness, hardness, corrosion resistance, thermal conductivity, and composition and structure are also required.
The main sectors that were stated to benefit from surface engineering were energy generation, transportation, and energy storage, with some interest in infrastructure and packaging.

The areas where better models and algorithms are required are the prediction of properties and performance, for processing, and for the prediction of in-service behaviour and lifetime.

Specific applications for engineered surfaces covered many different areas showing the widespread benefits of this industry.

The results from the study will be used to inform the development of new projects on metrology for surface engineering within the UK's National Measurement System and its delivery by NPL. It is intended that future work will continue the collaborations that have already been established particularly with industry, SELF and the EPSRC Network Plus on Digitalised Surface Manufacture (DSM) network, but also with the University of Southampton. The University of Manchester, and the Henry Royce Institute.

The results of the survey suggest that future work should focus on some of the key

measurements required for property and performance assessment such as wear and friction and adhesion testing. Thickness measurement also emerged as a method where further work is needed, but here there are many post processing methods available so either better information on available methods needs to be disseminated, or new methods developed for in process measurement where it can be used as a technique for close control during deposition.

A specific area where close collaboration will be required is to develop better in process measurement techniques. Since NPL does not have surface engineering processing equipment, a joint programme of work with an appropriate processing supplier will be needed if work on in situ measurements for processing can proceed.

All of these factors support the creation of a UK Centre for the Application of Metrology to Engineered Surfaces (CAMES). The role of the new centre would be to ensure the widest possible knowledge of the benefits of metrology for engineered surfaces and thereby to enable industry and other stakeholders to maximise the contribution that surface engineering technologies can make to the goals of net zero and sustainable use of materials. The centre would be established as a collaboration between NPL and the Royce Institute with the support of SELF and universities such as the Universities of Manchester and Southampton.

2 SURFACE ENGINEERING

Surface engineering is concerned with the modification of a surface to provide advantages in terms of functionality and performance. Surfaces can be engineered by many different processes including adding a coating to the surface by physical or chemical deposition, or by modifying the surface by physical or chemical processes. Surface engineering is used throughout manufacturing and engineering industry to enhance the surface of components that can then be made from low cost, lightweight materials.

A review of the Surface Engineering and Advanced Coatings industry [1] by a special interest group of the KTN identified that at the time, 2014, the UK’s engineering coatings industry was worth £11bn and affected products worth £140bn (Figure 1). Later analysis conducted in 2018 [2] showed that the surface engineering industry was very fragmented with many small SEMs as well as a few larger organisations. When full advantage was taken of the opportunity to optimise the industry it was expected that the industry would expand by 2025 to be worth £25bn affecting £313bn of products (Figure 2).

There are many characteristics of components that can be optimised through surface engineering, see box. These bring tremendous benefits to industry and society and have the potential to make a major contribution to the goals of achieving a net zero economy and sustainable use of materials through reductions in friction, increasing the durability of products, and enabling improved, more cost and energy effective design of products. For example, a recent analysis has concluded that 23 % of total worldwide energy is consumed by tribological contacts (either by overcoming friction or replacing worn parts) [3]; engineering surfaces can make a major contribution in reducing these losses (Figure 3).

Examples of characteristics optimised through surface engineering:

- Wear resistance
- Corrosion resistance
- Thermal insulation
- Oxidation resistance
- Chemical diffusion barrier
- Friction reduction
- Fatigue strength
- Electrical resistance
- Electrical Conductance
- Non stick
- Anti microbial
- Biocompatability
- Catalyst

As performance and lifetime requirements steadily increase, new advanced coatings are continually being developed. This is driven by the need to move towards a net zero carbon society with efficient and sustainable use of materials being a paramount concern. During the development of any new coatings, it is important for any new materials to be characterised to assess that they will be fit for purpose. It is too slow and expensive to take a blind application specific empirical approach to development. Optimising the processing and surface engineering of components also requires continual measurement to ensure that the final components meet the requirements of a design for manufacture (DFM) culture (Figure 4).

Indeed, it is extremely useful when any coated system is optimised, to have reliable data to feed into the development process. This is particularly true for the realisation of Industry 4.0 and digitalisation of design and manufacture where assured materials data on properties and performance are essential.

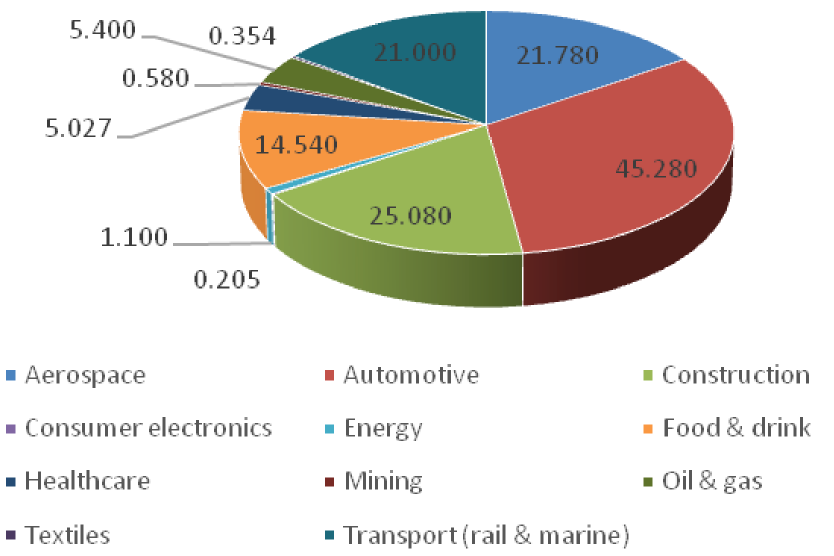

Figure 1: Value (£k) of products affected by surface engineering in 2014 [1].

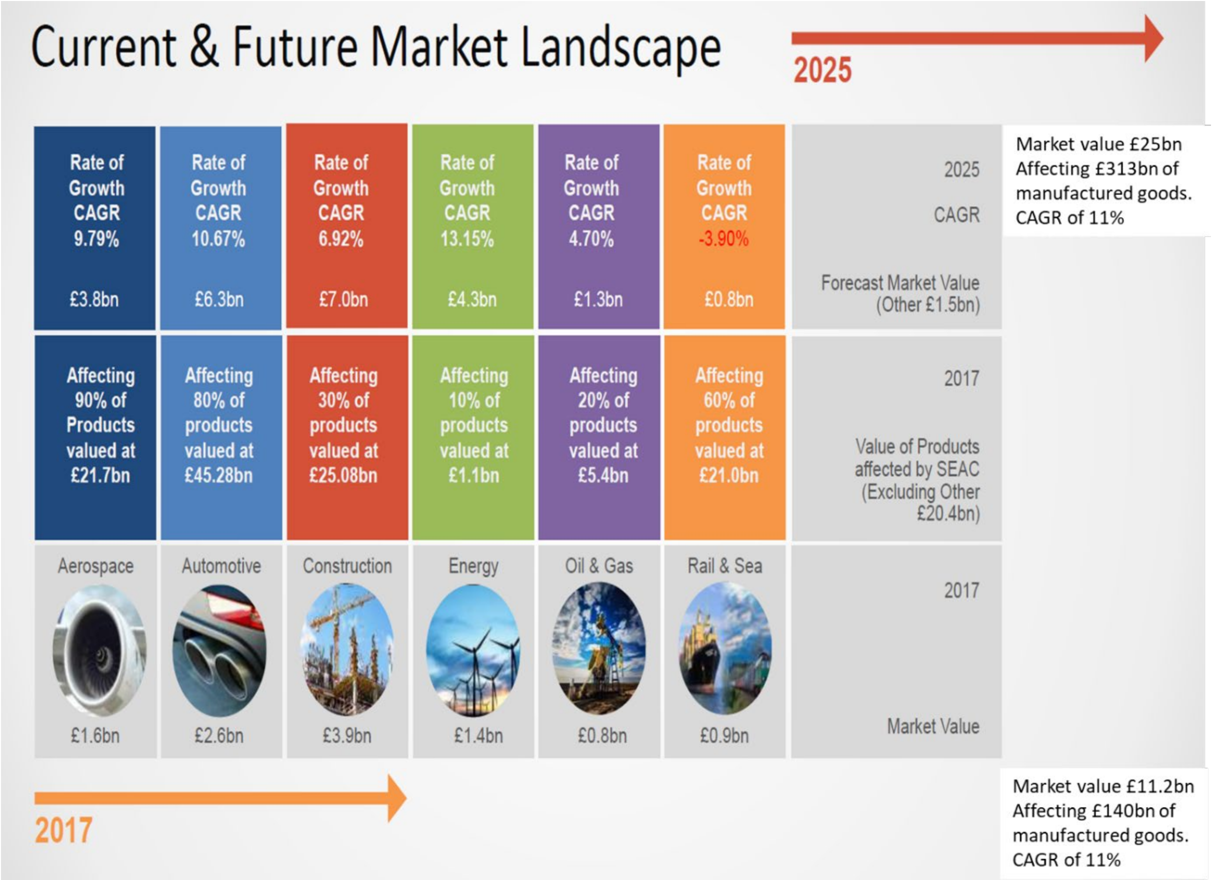

Figure 2: Current (2017) and future market landscape for surface engineering [2].

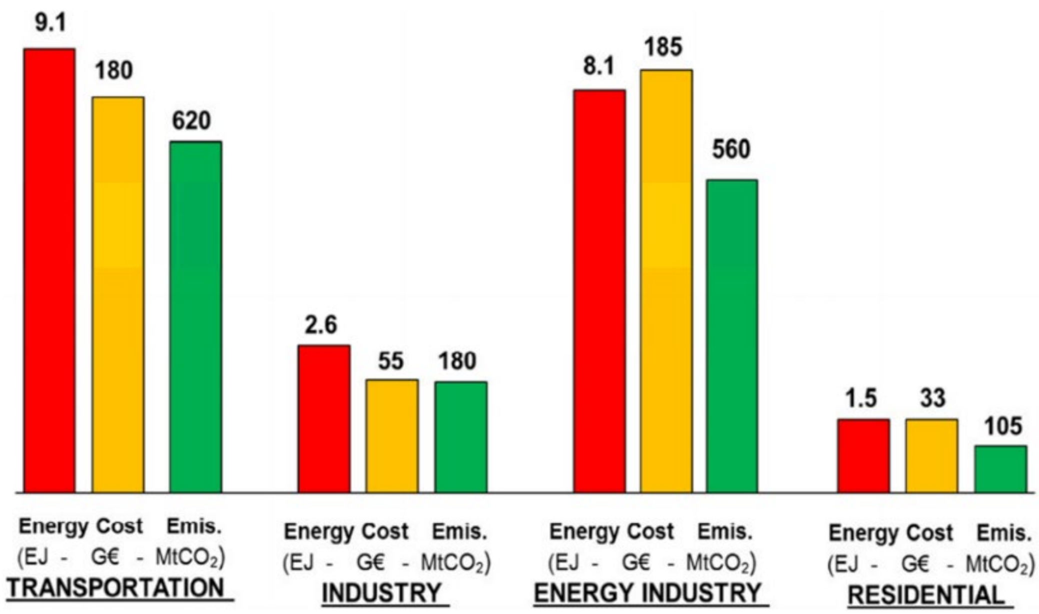

Figure 3: Potential annual energy, cost and CO2 emission savings globally estimated to be achieved after 8 years of intensive advanced tribology implementation [3].

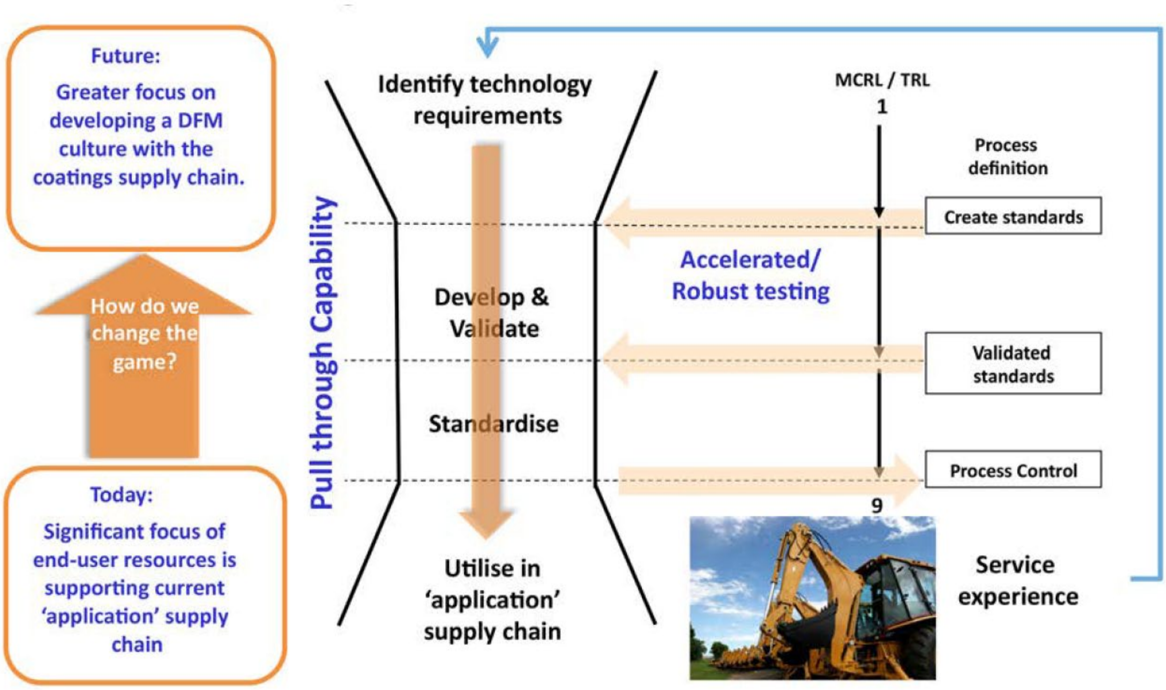

Figure 4 Product lifetime cycle for components with engineered surfaces [1]. TRL is technology readiness level, MCRL is manufacturing and commercial readiness level, DFM is design for manufacture.

3 INDUSTRY 4.0 AND DIGITALISATION

We are currently entering into the fourth industrial revolution where data driven manufacturing has become one of the major driving forces in manufacturing along with the development of the internet of things (IOT) and cyber physical systems (Figure 5). The real revolution within manufacturing that Industry 4.0 has introduced is the potential that industrial digitalisation can bring. The growing use of connected industrial processes, robotics, software and automation is leading to improved:

- Speed to market
- Productivity
- Quality
- Efficiency
- Strengthened supply chains

These are all critical to ensure success in an increasingly diverse and competitive market.

Industrial digitalisation enables the generation of value in the real world to take place based on information gained in the cyber world.

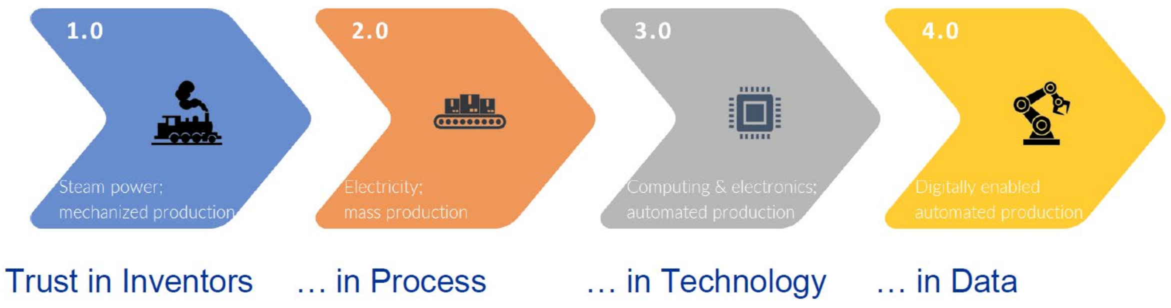

Figure 5: Illustration of progression to Industry 4.0.

4 ROLE OF METROLOGY

Data is the bridge between the virtual and real world and its quality determines its worth in generating real world value. Data underpins all aspects of manufacturing. As data is passed between devices, through processes and across organisations its provenance becomes increasingly important. A key role of metrology is to generate trusted data providing the required level of confidence. Trusted data is always dependent on high quality reliable measurement systems and their correct use. Providing confidence in data facilitates industry to realise more efficient design, test and manufacturing cycles, greater efficiencies in creation and delivery and fewer mistakes.

The transition to an industrially digitalised manufacturing landscape is seeing a step change in the volume of data collected and used in manufacturing. Increased reliance on data means that trust and confidence in data becomes a critical issue. Generating trusted data is dependent on having a good understanding of the measurement system that generated it. It is also important that the quality and any uncertainties in the data are well understood.

For organisations that design, test, make and use advanced materials and products incorporating engineered surfaces, the key goal is to provide highly trusted and traceable materials data that accelerates competitiveness, agility, productivity and sustainability (Figure 6). To achieve this many different aspects of how material measurements are achieved need to be considered (Figure 7) including the

- Materials and their history
- Testing procedures
- Test environment
- Test equipment
- People skills
- Health and safety
- Calibration
- Analysis and uncertainty evaluation
-

All this information needs to be recorded as the metadata for the measurements and needs to be treated as an intrinsic part of the data record along with the test results themselves. In materials testing there is normally a progression from initial considerations of the materials concerned through to eventual application of the data. This all contributes to the full design, test, make and use cycle (Figure 8).

Figure 6: Purpose and benefits of materials metrology.

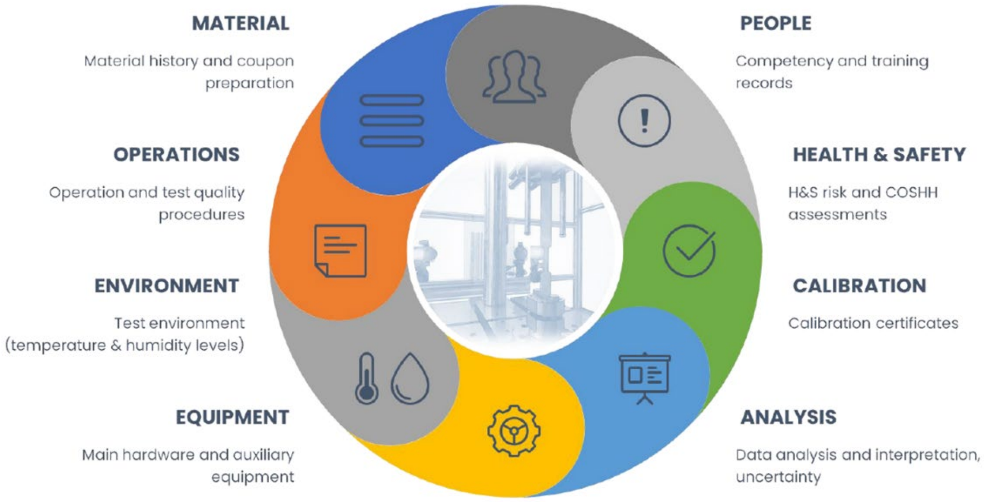

Figure 7: Holistic consideration of data.

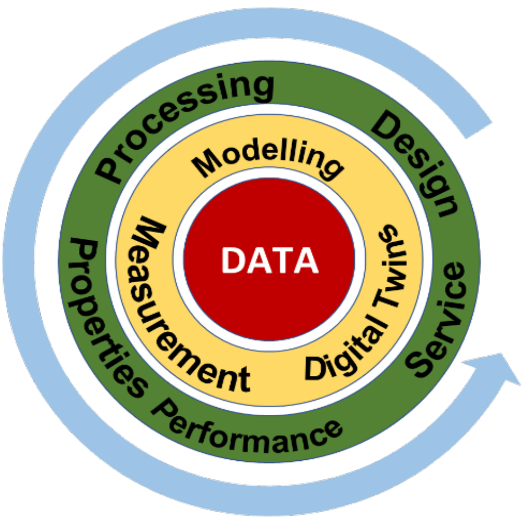

Figure 8, Relationship between data and life cycle for materials and products.

5 CONSULTATION EXERCISE

To gain more detailed information on the role of metrology in surface engineering, a consultation exercise was carried out with industry and other stakeholders, with the support of SELF and the EPSRC Networkplus on Digitalised Surface Manufacture.

The initial action was to discuss the role of metrology with the principle investigators of the EPSRC funded NetworkPlus on Digitalised Surface Manufacture (DSM) [4]. Following this, eight representatives from surface engineering firms were interviewed. Finally, a workshop was held with 24 stakeholders to get their views on key questions including:

- What properties do we most need assured data for?
- Which sectors need to be addressed?
- What are the specific applications within these sectors?
- How do we plan to use the data captured?
- What models and algorithms do we need to develop and implement?
- What do predictive twins look like?

The contacts made during the consultation exercise are given in Appendix 1, with the workshop agenda in Appendix 2.

6 RESULTING OUTCOMES

6.1 INITIAL DISCUSSIONS

The initial results from the discussions with the DSM NetworkPlus and industrial stakeholders confirmed that the development of trusted data was a crucial element that underpinned the whole design, manufacture, test and use cycle for engineered surfaces. This information was fed into the design of the workshop to ensure that the maximum benefit was obtained.

Specific insights were:

1) Properties. Most tests are destructive and are carried out on small coupons which are normally coated along with the components to be coated. Some properties are also very difficult to measure. Adhesion is a good example. It is still very difficult to obtain good measurements of coating adhesion. It is also difficult to relate the data obtained from tests to performance in applications.

2) Data handling. It is important to know how we will feed this data into useable data stores (managing the data through digital integration). How do we want to use the data? Are there possibilities for commercial data storage solutions, and which market sectors do we want to address?

   A major issue is that there are many requirements for surface engineering as virtually everything has an engineered surface. This surface engineering is carried out through either the application of a coating or finishing in some way to meet a functional or aesthetic requirement. There is also an incredibly large range of engineered surfaces solutions. There are many different processing routes with tailored compositions to address the needs.

   There have been several expert systems for surface engineering attempted in the past, but these have never had that much take up. Matching solutions to need normally relies on advice from experts. It is crucial that any data that is generated can be assured, and its relevance to applications understood.

3) Modelling and analysis. We need models for service behaviour, processing, and prediction of properties and performance. Models can be empirical or physically based. Empirical models are based on collection of large amounts (hopefully) of data – useful in complex systems where you cannot develop a reasonable physical understanding. Process models depend on the type of process used.

   There are some physically based property and performance models available for a range of properties. It is likely that as the complexity of the system increases that there are less models available. As an example, in tribology, erosion from solid particles is relatively well understood with many models that fit empirical data quite well. By contrast, sliding wear is a combination of complex phenomena which are poorly understood and there is a lack of good models here.

   An important overall aim for both empirical and physically based models is to relate complex behaviour to parameters that are simple to measure.

4) Digital Twins. It is important to consider how we want to use digital twins and what benefits we want to achieve from their use. How robust are digital twins? What is the quality of the underlying models and how do we ensure that the digital twins are validated?

6.2 WORKSHOP

Based on the insights gained from the initial discussions with stakeholders the questions that were asked to participants at the workshop were:

- what properties do we need assured data for (physical measurements & data collection)?
- how will we feed this data into useable data stores (managing the data through digital integration)?
- what models, algorithms we must develop and implement (virtual models using the data for validation)?
- what predictive digital twins would look like (bringing everything together to make informed data-driven decisions)?
-

The initial part of the workshop used the interactive software Mentimeter to allow all the workshop participants to enter their response interactively as questions were asked. This was followed by a discussion between the participants.

With respect to the properties of engineered surfaces, the highest interest was shown in tribological performance such as wear and friction, and measurements of the adhesion of coatings. The measurement of coating thickness, hardness, corrosion resistance, thermal conductivity, and composition and structure were also considered to be important (Figure 9). Discussion revealed that most participants thought that process optimisation would be an important use of the data gathered though measurement. The data would also be used for quality assurance and would have to have traceability, provenance and certification. It would also be used in the prediction of service life and for product development through better design. It would also be important to have assured data to build and then validate models. Standards would be necessary to ensure that robust relevant data could be obtained repeatably and reproducibly. An important requirement that even once assured data becomes available it needs to be made accessible through common frameworks for storage with appropriate mechanisms to ensure that aspects such as commercial value are considered.

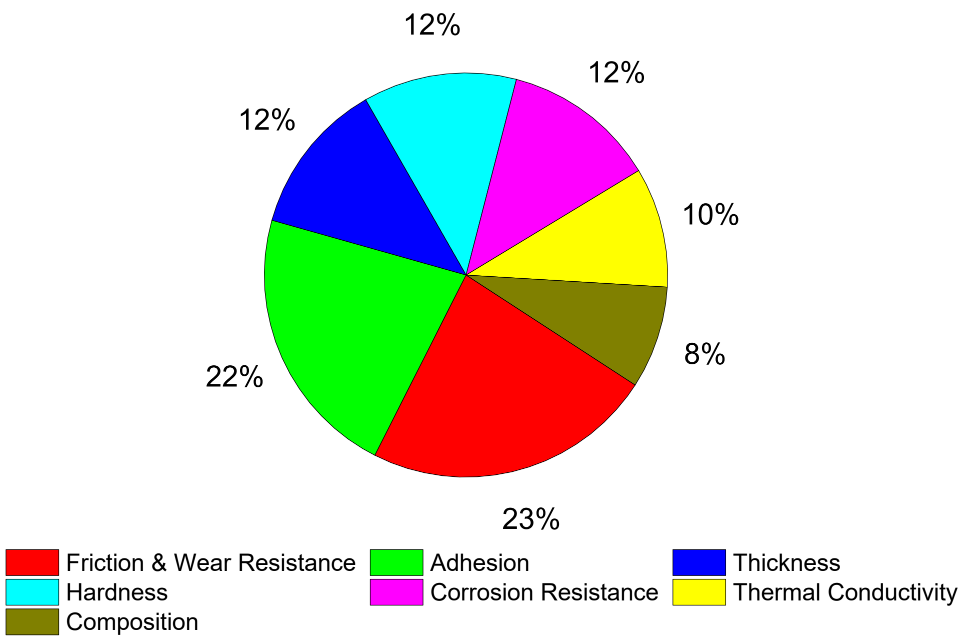

Figure 9, Most important properties where assured data is required.

The main sectors that were stated to be of relevance for surface engineering were in energy generation, transportation, and energy storage, with some interest in infrastructure and packaging (Figure 10). However, when different applications for engineering surfaces were discussed a very wide set of applications were suggested, showing that surface engineering is relevant almost universally across industry (Figure 11).

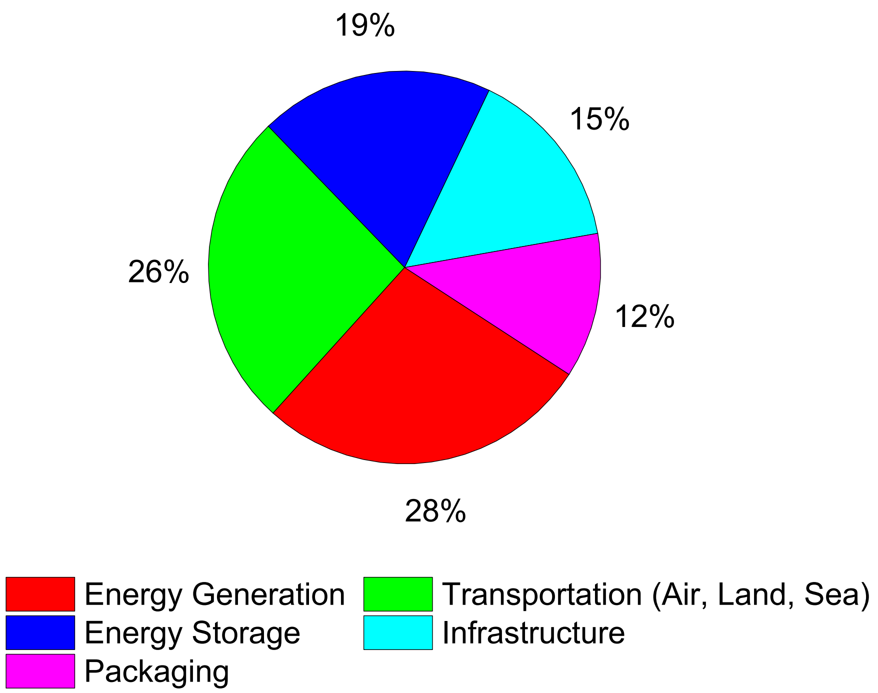

Figure 10, Main sectors of relevance to surface engineering.

Figure 11, Specific applications given for engineered surfaces.

Better models and algorithms were felt to be required across all areas including the prediction of properties and performance, for processing, and for the prediction of in-service behaviour and lifetime (Figure 12). When incorporated into digital twins it was felt that there was a wide range of desirable aspects including:

- Digital twins should be data rich, interconnected, and able to integrate with physical reality in a meaningful way
- Ability for real time updated predictive lifetime performance and failure prediction
- Simulation and control of processes
- Incorporate models compatible with engineering design
- Ability to give a live state of an asset and engineered surface informed by data collected from the physical product
-

The availability of robust digital twins would enable many benefits including:

- Providing confidence to customers
- The selection of materials and coatings for specific applications
- Becoming an aid to decision making, reducing the dependence on tacit knowledge and beginning to address the loss of knowledge from the community as people retire
- Simulation of processing to enable better processing optimisation
- Reduction in the cost of testing
- Creation of agile digital standards and help with the certification and accreditation of products and services
- Simulation of in-service degradation / failure modes to enable improved material and coating selection and optimisation

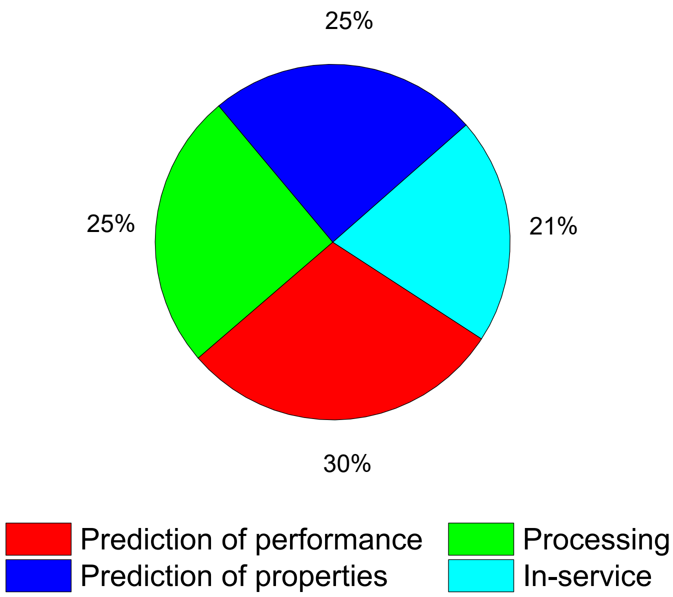

Figure 12, Application areas where models and algorithms need to be developed.

7 CONCLUSIONS

The results from the study will be used to inform the development of new projects on metrology for surface engineering, to be delivered within the National Measurement System, at NPL. It is intended that future work will continue the collaborations that have already been established particularly with industry, SELF and the DSM network, but also with the University of Southampton, the University of Manchester, and the Henry Royce Institute. The results of the survey suggest that future work should focus on some of the key measurements that are required for property and performance assessment such as wear and friction and adhesion testing. Thickness measurement has also emerged as a method where further work is needed, but here there are many post processing methods available so either better information on available methods needs to be disseminated, or new non-destructive methods developed that can be used for in process measurement where it would be useful as a technique for close control during deposition.

A specific area where close collaboration will be required is to develop better in process measurement techniques. Since NPL does not have surface engineering processing equipment, a joint programme of work with an appropriate processing supplier will be needed if work on in situ measurements for processing can proceed.

There is clearly considerable interest in the development of digital twins which were seen to be essential future tools in the development of the surface engineering industry. Their adoption, based on the generation and use of assured data through good metrological practice, will ensure that the benefits of Industry 4.0 for improved materials development, efficient processing and effective application of engineered surfaces.

All of these factors support the creation of a UK National Centre for the Application of Metrology to Engineered Surfaces (CAMES). This would be established as a collaboration between NPL and the Royce Institute with the support of SELF and universities such as the Universities of Manchester and Southampton. The role of the new centre would be to ensure the widest possible knowledge of the benefits of metrology for engineered surfaces and, thereby, to enable industry and other stakeholders maximise the contribution that surface engineering technologies can make to the goals of net zero and sustainable use of materials.

8 ACKNOWLEDGEMENTS

The authors would like to acknowledge the help that was obtained from the experts consulted in this exercise that are listed in Appendix 1, and would also like to thank the Department of Business, Energy and Industrial Strategy for funding from the National Measurement System.

9 REFERENCES

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2) Surface Engineering and Advanced Coating: A Transformational Journey to Sustainable Growth, Surface Engineering Leadership Forum, 2018
3) K Holmberg, A Erdemir, Influence of tribology on global energy consumption, costs and Emissions, Friction 5(3): 263–284 (2017), https://doi.org/10.1007/s40544-017-0183-5
4) https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/S036180/1

10 APPENDIX 1

Principal Investigators NetworkPlus on Digitalised Surface Manufacturing:

Allan Matthews	University of Manchester / Royce Institute
Ash Tiwari	University of Sheffield
Saurav Goel	London South Bank University
Adrian Murphy	Queens University Belfast

Industry experts consulted in survey:

Bryan Allcock	TRL9 Ltd	CEO
Henry Begg	TWI Ltd	
Yuri Zhuk	Hardide Ltd	CEO
Richard Wellman	Rolls Royce	
Laurent Espitalier	Harkness Screens	Technical Director
Kevin Cooke	IET	Chair IET Tribology Technical Comm, ex technical director Teer Coatings Ltd
David Rickerby	Cranfiled University	Ex Rolls Royce

Workshop participants:

Allan Matthews	Manchester University	Director DSM Network, SELF member
Dave Elliott	IMF	IMF, Chair SELF
Bryan Allcock	TRL9	Member SELF
Ping Xiao	Manchester University	Chair IOM3 SED, SELF member
Robert Quarshie	KTN	Member SELF
David Rickerby	Cranfield University	Member SELF
Geoff Hale	Secretary of SELF	
Richard Wellman	Rolls Royce	IOM3 Surface Engineering Board
Henry Begg	TWI	IOM3 Surface Engineering Board
Robert Wood	University of Southampton	IOM3 Surface Engineering Board
Tanvir Hussain	University of Nottingham	IOM3 Surface Engineering Board
Chris Walker	Diamond Hard Surfaces	Director, CEO
Jinlong Yin T	eer Coatings	Research team leader
Laurent Estipalier	Harkness Screens	Technical Director
Yuri Zhuk	Hardide Ltd	CEO
Su Varma	NSG (Pilkington)	
Liam Blunt	Huddersfield University	Metrology Hub
Nathan Roberts	Nottingham University	
Mingyu Liu	Nottingham University	
Adrian Murphy	Queens University Belfast	DSM Network
Mark Gee	National Physical Laboratory	
Gareth Edwards	National Physical Laboratory	
Tony Fry	National Physical Laboratory	
Stefanos Giannis	National Physical Laboratory	
Tim Kamps	National Physical Laboratory	

11 APPENDIX 2: WORKSHOP AGENDA

Workshop: Role of Metrology in the Digitalisation of Surface Engineering
National Physical Laboratory
8th December 2020

Agenda

10:30 Introductions, Mark Gee, NPL

10:45 Introduction to the EPSRC NetworkPlus on Digitalised Surface Manufacturing, Allan Matthews, Manchester University

11:10 Digital Manufacturing and Measurement, Stefanos Giannis, NPL

11:35 Surface Engineering Metrology at NPL, Mark Gee, NPL

12:00 Lunch

13:00 Introduction to Workshops, Mark Gee, NPL

13:15 Workshops, All

Questions:

- what properties do we need assured data for (physical measurements & data collection)
- how will we feed this data into useable data stores (managing the data through digital integration)
-
- what models, algorithms we must develop and implement (virtual models using the data for validation)
- how predictive digital twins would look like (bringing everything together to make informed data-driven decisions)

14:30 Feedback, Facilitators

15:00 Close