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Safe and sustainable development of advanced materials: UK National Knowledge Sharing Network Workshops†

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The term advanced materials (AM) is used widely to cover a large number of diverse new innovative materials, including nanomaterials, advanced composites, innovative surface coatings, (bio)polymers, porous and particle systems, ceramics, smart and metamaterials and advanced fibres and textiles. With any new materials, there are commercial and performance advantages that need to be balanced with any potential environmental, health and safety issues, for example, around exposure, toxicity, sustainability and waste. Key players in the UK from government bodies, research, measurement and standardisation organisations, academia and industry came together to consider these issues *via* two online workshops in April 2021 and February 2023. At each event, scene-setting presentations by key experts were followed by discussions addressing salient issues, including, benefits and barriers to AM commercialisation, potential environmental, health and safety issues, and safe(r) by design approaches. The first workshop served as a starting point to share views on the potential societal benefits of AM and perceived obstacles to their wider adoption. The second workshop focused on safety by design, life cycle analysis and challenges faced at different points in the supply chain. In addition to confirming findings from previous studies, these workshops also highlighted specific challenges that are faced by small to medium sized enterprises (SME). These workshops provided a unique opportunity for policy makers, regulators, standardisation bodies, funding bodies and academia to understand the concerns of industry and researchers, who develop and work with AM. This included what they felt would help support them in their aims of developing innovative, commercially successful, safe and sustainable AM.

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Environmental significance

The term advanced materials (AM) is used for many diverse innovative materials, which have the potential for significant product performance improvement and commercialisation. However, with any new materials, there are potential environmental, health and safety concerns, for example, around toxicity, sustainability and waste. These must be addressed appropriately at an early stage to prevent potential damage to human health and the wider environment. Key UK experts from government bodies, research, measurement and standardisation organisations, academia and industry came together in two workshops to consider needs for the commercialisation of AM. The findings, including the importance of safe(r) and sustainable by design approaches, will support the environmentally safe and sustainable development of AMs.

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1. Introduction

The term advanced materials (AM) has been coined and is generally used to describe a large number of diverse new innovative materials and modifications to existing materials for new applications. Although there remain issues with the definition of the term, which we explore below, it is typically applied to a wide range of material groups and categories, including nanomaterials, advanced composites, innovative surface coatings, (bio)polymers, porous and particle systems, ceramics, smart and metamaterials, and advanced fibres and textiles. Each advanced material is tailored to a specific application, and benefits can include environmental benefits, lightweight structural materials and improved mechanical properties.

The global AM market was estimated to be valued at ca USD 500 billion in 2023 and is projected to reach USD 700 billion by 2028.[1] Given their significant potential, governments and national and international organisations have recently increased focus on the industrial and economic possibilities of AM. For example, the UK Innovation Strategy identified 'advanced materials & manufacturing' as one of seven key 'technology families'[2] and advanced manufacturing is a priority of the UK Science and Technology Framework.[3] In Europe the industry led 'Advanced Materials 2030 Initiative'[4] is one of the two conceptualizing entities together with the 2D Materials Initiative (2DMI) behind 'Innovation Materials for Europe'(IAM4EU). IAM4EU, is the European Commission's latest public-private partnership set for 2025–2027 under Horizon Europe Materials for Europe. With any new material, there are benefits of potential performance upgrades and commercialisation, but these need to be balanced with potential environmental, health and safety (EHS) concerns, for example around toxicity, exposure, sustainability, waste and end-of-life. How to address these important factors, and other related issues, including terminology, standards and regulatory requirements for AM is being considered by key national and international organisations, including the Organisation for Economic Co-operation and Development (OECD) and the International Organization for Standardization (ISO). This work on AMs is not being undertaken in a vacuum. The strong international pressure for a sustainable and circular economy for all chemicals and products, in which safe and sustainable by design (SSbD), recyclability and re-use are high on the agenda, is a major driver.

Terminology is important, however, developing agreed definitions of AMs has proven complex.[5] The term has been around since the 1950s, but one of the earliest definitions is from a project sponsored by the US Bureau of Mines in the late 1980s, which stated that advanced materials 'are those that possess novel or unique properties, or exhibit greater mechanical, thermal, electrical, optical, chemical properties' relative to traditional materials.[6] The Journal Advanced Materials was also launched at around this time. Discussions around definitions have also appeared as part of projects in the 2010s to facilitate dialogue between advanced materials developers and designers (Design and Advanced Materials As a Driver of European Innovation, DAMADEI)[7] and more generally around knowledge and technology transfer in materials science.[8] Kennedy *et al.*[5] undertook a useful examination of existing definitions and through expert workshops developed a definition that goes beyond simple material science aspects to encompass EHS concerns which may be of use to professionals in that field – "*Advanced Materials are materials that are specifically engineered to exhibit novel or enhanced properties that confer superior performance relative to conventional materials. As a result of their unique characteristics, advanced materials have a highly uncertain hazard profile and the potential to require special testing procedures and methods to assess potential for adverse environmental health and safety impacts*". The ISO Technical Committee (TC) 229 (Nanotechnologies) is developing international standards for nanotechnologies[9] including a definition for AM, which may change as consensus is reached. In its current draft form, an AM is defined by ISO as a "*material with significant improvements in properties or performance for a specific application*". Associated with this are many informative notes, which state that: "*some advanced materials gain their improved properties through modification of their internal or surface structure; some, but not all, advanced materials are created by advanced technologies; some, but not all, nanomaterials are advanced materials; and, advanced materials can be, but are not always, complex and highly engineered materials*". It importantly notes that "*materials that are considered advanced materials today are anticipated to be displaced or to become conventional materials in the future*". Such efforts to develop a definition are clearly welcomed but issues such as the temporal nature of the definition may potentially remain a challenge to practical application in some contexts.

Other organisations have not attempted a formal definition but have considered a more descriptive approach. For example, the OECD has developed a working description of the term advanced materials (for which they use the abbreviation AdMa).[10] The working description in summary is: "*AdMa are understood as materials that are rationally designed to have new or enhanced properties, and/or targeted or enhanced structural features with the objective to achieve specific or improved functional performance. This includes both new emerging manufactured materials, and materials that are manufactured from traditional materials. This also includes materials from innovative manufacturing processes that enable the creation of targeted structures from starting materials, such as bottom-up approaches. It is acknowledged that what are currently considered as AdMa will change with time*".[10] In addition, the OECD has broadly grouped current AM into nine different material categories: biopolymers, composites, porous materials, metamaterials, particle systems, advanced fibres, advanced polymers, advanced alloys, and smart nanomaterials,[10] and is also exploring SSbD[11] and collaborative development approaches[12] for AM.

In Europe there is also a focus on issues of safety and sustainability for AM. The industry led 'Advanced Materials 2030 Initiative' is billed as a 'multi-sectoral accelerator for the design, development and uptake of safe and sustainable advanced materials towards a circular economy'.[4] The European Commission (EC) states that it supports research and innovation for chemicals and advanced materials as this is key to achieving safe and sustainable development.[13] Their 'strategic research and innovation plan for safe and sustainable chemicals and materials'[14] was formed from extensive consultations with different stakeholder groups to guide funding decisions. The EC has also published a recommendation establishing a European assessment framework for 'safe and sustainable by design' chemicals and materials[15] and is funding work on risk governance[16] and SSbD for AM.[17]

National organisations across the globe are also addressing requirements for the successful and safe development of AM. For example, in the USA, the National Institute for Occupational Safety and Health (NIOSH) emphasise the term advanced manufacturing,[18] stating that this "involves using new materials, processes, and management methods to improve the development and manufacture of products". Some of these technologies include additive manufacturing, nanotechnology, biological manufacturing & synthetic biology and advanced materials. NIOSH is exploring how to promote responsible development and use of advanced manufacturing technologies, stating that their work began with nanomaterials and has expanded to 3D printing and robotics.

The German Environment Agency (UBA) organized a series of thematic conferences from 2019 to 2021 to address questions on AM with regard to chemical safety and sustainability over the whole life cycle of their applications.[19] They categorised AM into the following groups: advanced alloys, advanced polymers, biopolymers, porous materials, particulate systems, novel fibres, composites, metamaterials and nanomaterials.[20] Following on from the conferences, UBA published reports on risk governance for AM[21] and also developed a position paper on advanced materials,[22] highlighting the requirements for a safe and sustainable lifecycle for AM.

The Japanese government materials innovation strategy from 2021 focuses on initiatives in four areas 1) creation and enhancement of a data-centric platform for materials research and development, 2) strategic promotion of key materials technologies and implementation areas, 3) creation of a materials innovation ecosystem, and 4) training and recruitment of talent to support materials innovation capacity. These were developed by considering four perspectives: i) materials informatics, ii) manufacturing process technology, iii) circular economy (resource recycling), and iv) material resources.[23] The strategy highlights several activities related to sustainability and a circular economy and highlights various AM, including semiconductors and next-generation bio and polymer materials.

Korean researchers attribute South Korea's advancement in materials technology to the efforts of their government by heavily funding the area and placing South Korea at the top of the international ranking for research and development expenditure as a percentage of gross domestic product (GDP).[24] They also partly attribute growth in their manufacturing industry to strong relationships between academia and industry allowing rapid developments in emerging technologies especially in semiconductors and displays but also future industries, including energy and eco-friendly sectors.

Within the UK, significant research funding is also being directed towards AM development, particularly with the creation of the Henry Royce Institute (**https://www.royce.ac.uk**) as the UK national institute for advanced materials research and innovation. The national funding body UK Research and Innovation (UKRI) has an Advanced Materials theme that identifies the following key research areas for AM:[25] biomaterials and tissue engineering, condensed matter: electronic structure, condensed matter (magnetism and magnetic materials), functional ceramics and inorganics, graphene and carbon nanotechnology, ceramics, composites, metals and alloys, materials for energy applications, photonic materials, polymer materials, superconductivity and spintronics. Another area of expected increased funding is on semiconductors, following announcement of the UK Semiconductor Strategy[26] and identification of this area as one of 5 critical technologies in the UK Science and Technology Framework.[3] The importance of addressing EHS and sustainability considerations is clearly recognised. For example, in the UK Innovation Strategy,[2] 'Advanced Materials & Manufacturing' was identified as one of the seven key 'technology families' and it was further stated that for AM – "*learning to manufacture these materials at scale and incorporating safety and sustainability into their design and innovation, is as important as their discovery and development. This effort is essential to unlocking innovation across all major industrial sectors*".

We think it is important for material scientists, industry, and regulators to consider how to work best together to support the safe development and use of AM in order to balance commercial and performance advantages with any potential environmental, health and safety issues, *e.g.*, around exposure, toxicity, sustainability and waste. Thus, key players in the UK from government, government organisations, academia and research and measurement and standardisation organisations came together to study the development of AM in the UK *via* two workshops. The aim was to create a knowledge sharing community and to help feed into UK domestic policy, for example on innovation and chemicals.

In this paper, we summarize, discuss and analyse the contributions from participants at two UK workshops on the safe and sustainable development of AM and discuss common themes arising. These represent the views of the individual participants at the time of the meeting where a range of views were expressed on the general UK and wider international needs. As such the views reported should not be interpreted as the views of the authors or organisers. Although in most cases there was a high degree of agreement, not all participants stated that they agreed with all points, so the views contained cannot be considered consensus views of all the participants. In addition, opinions and new issues may have come up since or may come up in the future. In some places in the paper, the authors have added additional notes to provide additional information that may be helpful to the reader. The topics discussed at the workshops included a) the definition of AM, b) the main barriers to the development and commercialisation of AM, c) SSbD tools and whether they are being used, and d) EHS concerns, particularly at the end-of-life of AM.

These workshops can be considered complementary to other activities to understand the UK AM ecosystem, such as the recent UK government call for evidence on UK Advanced Materials.[27]

2. Methods

In 2020, representatives from several UK government bodies, research, measurement, and standardisation organisations (Defra, HSE SD, NPL, UKHSA and BSI) came together to discuss issues surrounding the safe and sustainable development of AMs. It was agreed that the development of a knowledge sharing network was important with the representatives acting as the organising committee. A starting aim was the understanding of the important issues within the UK context. Holding online workshops with key players in the UK from government bodies, research and measurement and standardisation organisations, academia and industry was considered a practical way to move this initiative forward. Details on two online workshops are given in the next section.

2.1 First workshop

The first workshop was held on 23 April 2021. The event was invite-only with potential attendees identified through relevant contacts and intended to attract contributions from all relevant stakeholder sectors, including those from government, measurement and standards institutes, universities, research institutes, trade bodies and industry (large companies and small to medium enterprises (SME)). Approximately 70 potential attendees were identified and in total over 55 people attended the workshop from more than 30 organisations (Table 1). The format of the workshop included an initial introduction outlining the objectives of the workshop followed by a series of short scene-setting presentations, addressing terminology and standards, AM benefits, EHS, plastics, and the circular economy (details in Table 2). Presenters were requested to use a limited number of slides to maximise discussion. This was followed by an interactive group exercise using an online polling tool, where the following questions were posed to seek participant views:

- What sector do you represent?
- What do you define as an advanced material?
- What are the benefits to commercialisation of advanced materials?
- What are the barriers to commercialisation of advanced materials?
- What are the barriers to create advanced materials that are both safe and sustainable by design?

The results were output from the online polling tool as word clouds. The attendees were then split into five break-out groups, each with a maximum of ten participants and, with assistance from a facilitator, each group discussed the same three questions:

- What do you define as an advanced material?
- What are the barriers and benefits to commercialisation of advanced materials and how can advanced materials contribute to a net zero economy?
- Are Advanced Materials eco-friendly and are they a part of a circular economy? How can we create Advanced Materials both safe and sustainable by design?

Each group considered these questions in a different order and a member of the organising team summarised the

Table 1 Organisations attending the workshops

Sector	Organisation
Government	Department of Food and Rural Affairs (Defra), Health and Safety Executive (HSE), UK Health Security Agency (UKHSA), Food Standards Agency (FSA), Department for Business, Energy and Industrial Strategy (BEIS), Environment Agency[b]
Measurement and Standards Institutes	National Physical Laboratory (NPL), British Standards Institute (BSI)
Industry and Trade Bodies	Pilkington (NSG Group), BP, Oxford Instruments Plasma Technology,[a] Lloyds Register,[a] Avalon Consultancy Services,[a] Nanotechnology Industries Association, Nissan Motor Co Ltd,[a] British Coatings Federation,[a] Micro Materials Ltd,[a] Graphene Engineering Innovation Centre (GEIC),[a] Thomas Swan Ltd,[a] Applied Graphene Materials, Surface Engineering Association,[a] AWE,[a] BREC Solutions,[a] Promethean Particles,[b] Lucideon,[b] James Kent,[b] Malvern Panalytical,[b] Sandberg LLP,[b] British Plastics Federation,[b] Composites UK,[b] Dragonfly Insulation Ltd,[b] Perspectives Economics,[b] Versarien PLC,[b] Yordas Group,[b] Plastribution Ltd,[b] Advanced Material Development,[b] Materion UK Ltd,[b] IOM,[b] Saga Robotics,[b] Materials Nexus,[b] Leonardo Helicopters,[b] Nuclear AMRC[b]
Universities and Research Institutes	University of Manchester, Swansea University, Henry Royce Institute, Edinburgh Napier University,[a] Imperial College London,[a] University of Birmingham, University of Cambridge, Nottingham Trent University,[b] Graphene Engineering Innovation Centre Manchester,[b] University of the West of England,[b] University of Sheffield,[b] University of Surrey,[b] University of Lincoln,[b] University of the Arts London,[b] Heriot-Wat University,[b] University of Strathclyde[b]
Other	Engineering and Physical Sciences Research Council (EPSRC),[a] UK Research and Innovation (UKRI),[a] Innovate Knowledge Transfer Network (KTN)

[a] First Workshop only. [b] Second Workshop only.

Table 2 Scene-setting presentations at the first and second workshops

Presentation topic	Speaker
First Workshop, 23 April 2021	
What do we understand by advanced materials – terminology and standards	Denis Koltsov (Chair ISO/TC 229 & BREC solutions)
Why advanced materials?	Phil Withers (Henry Royce Institute)
Why advanced materials?	Robert Quashie (KTN)
Potential health and environmental aspects – interface between regulators and materials technology	Delphine Bard (HSE)
Sustainability issues in novel and new materials	Sally Beken (KTN)
Sustainability and systems: from depolymerisation to policy	Mike Shaver (UoM)
Second Workshop, 7 February 2023	
Why advanced materials	Robert Quarshie (KTN)
Challenges in the production phase of advanced materials – thinking about life cycle assessment	Selina Ambrose (Promethean Particles)
Considering safety by design as a regulatory consultancy for SME's using advanced materials	Neil Hunt (Yordas Group)
Graphene regulations and exposure scenarios	Stephen Hodge (Versarien plc)
Implementing the UK innovation strategy	Izzy Webb (BEIS)
Challenges in moving from traditional polymers to more sustainable materials: meeting the required specifications to make materials work commercially	Dan Jarvis (Plastribution Ltd)

discussions. The break-out groups then came together and the key points from each discussion group were presented. During the final discussion session, the participants were asked two final questions using the online polling tool:

• What would you find useful as a follow up topic for a future meeting related to safe development of Advanced Materials?

• How can we exchange information more effectively about this subject in future?

2.2 Second workshop

The second workshop was organised by broadly the same organising committee (Defra, NPL, HSE, UKHSA, BEIS, BSI), however, increased effort was spent on identifying targeted industrial participants through greater engagement with industry bodies. It was held online on 7 February 2023. The event was again invite-only with potential attendees identified through relevant contacts and intended to attract contributions from all relevant stakeholders. Approximately 115 participants registered for the online workshop from over 30 organisations (Table 1) with around 50 delegates joining on the day.

The format of the workshop was similar to that of the first workshop, including an initial introduction outlining the objectives followed by a series of short scene setting presentations addressing, AM benefits, life cycle challenges, SSbD, graphene, the UK Innovation Strategy and sustainable polymers (see Table 2). The attendees were then split into 5 break-out groups. Each group discussed the same set of 3 questions. These were chosen to complement and build upon the first workshop with the organising committee deciding for discussions particularly on SSbD that grew in community interest since the first workshop. The questions asked were:

• **What are the main obstacles** do you foresee (as non-industry), or do you face (as industry), when considering or developing new advanced materials? What support could be offered to overcome these obstacles?

• How could you, or do you, **apply the concept of safe(r) by design** when working with or developing new advanced materials? Have there been any useful tools you have used so far? What support could be offered to encourage the use of safety by design?

• What do you foresee, or do you face, **environmental, health and safety obstacles when considering the end-of-life, of new advanced materials?**

3. Results and discussion

3.1 First workshop

3.1.1 Interactive group exercise. The interactive group exercises were run using the online polling tool AhaSlides (**https://www.ahaslides.com**). In the online workshop, participants were asked 5 questions as detailed above, one after the other and were allowed to submit multiple responses to each question. The word clouds produced are presented here and in the ESI.† The range of participants (Table 1) at the workshop was reflected in the responses to the question on sectorial representation (Fig. S1†).

There were 111 responses to the question – What do you define as an Advanced Material? (Fig. 1). A wide range of responses were received, which reflects the complexity of the field. Some of the responses related to specific classes of materials including 'composites' and 'nano' or 'nanomaterials'. Many responses were general with frequent use of the words 'novel', 'multi component', 'functional' and 'engineered', but with different wording in some cases. Note, Fig. 1 has had limited preprocessing of the responses prior to generating the word clouds in order to group similar terms and harmonise.

The most popular of the identified benefits of the commercialisation of AM were sustainability and competitive advantage (Fig. S2†).

There was a wide range of responses to the question on barriers to commercialisation, including terms related to

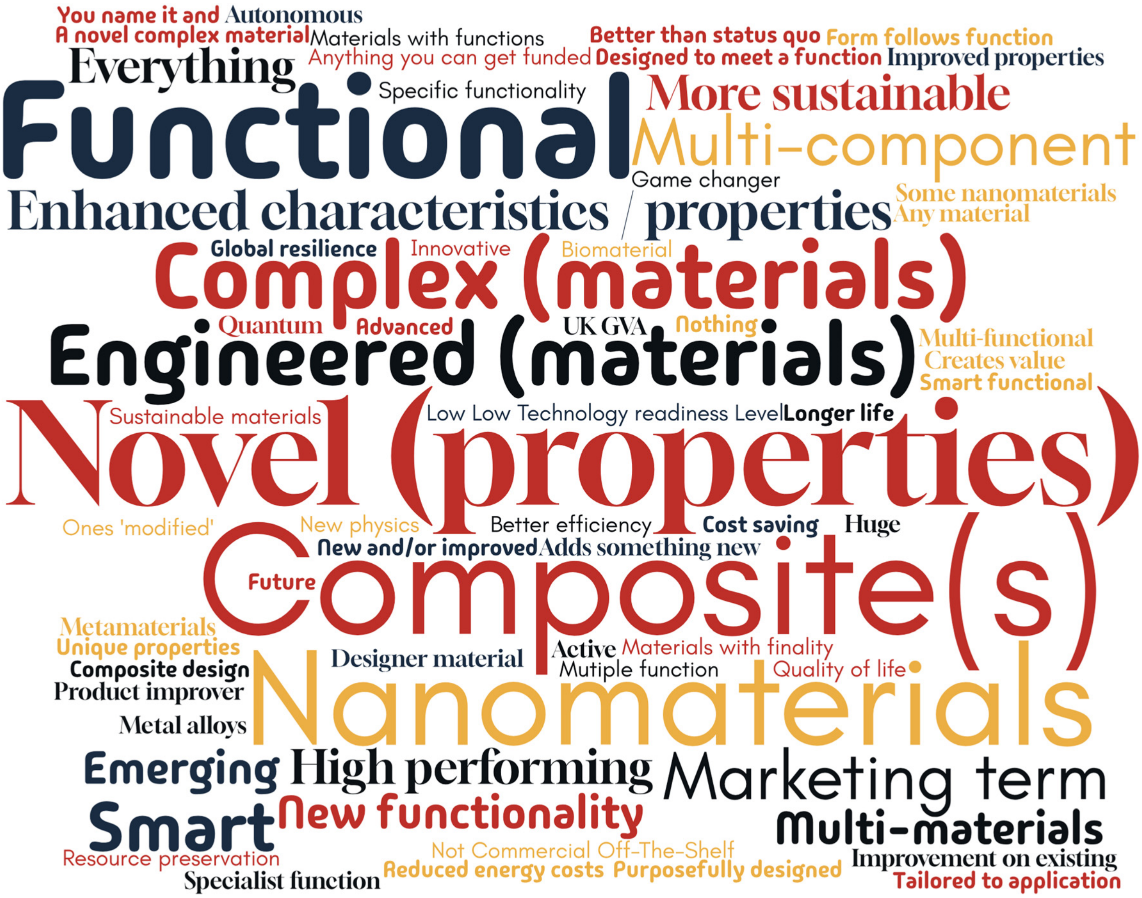

Fig. 1 Word cloud response to the question – *What do you define as an Advanced Material*? (111 responses). Note that limited preprocessing of responses was undertaken prior to generating word clouds to group similar terms and harmonise.

trust and acceptance by society, but the two most popular were understanding legislation and finance (Fig. S3†).

The final question in this session on the barriers to creating AM that are both safe and sustainable by design also received a wide range of responses with the most popular being funding, with skills and regulation a close second (Fig. 2). The concern around finance and skills is consistent with findings from the UK Government's call for evidence on UK Advanced Materials,[27] which found, for example, that contributors had noted a supply gap in the pipeline for relevant talent and skills in AM. Skills have also been highlighted as a concern by others. For example, the US National Strategy for Advanced Manufacturing was developed following public outreach and included goals related to improving and enhancing the skills base.[28]

3.1.2 Focussed discussion sessions. Participants were split into breakout groups, led and facilitated by members of the organising committee, and discussed three questions, which are listed below along with a summary of the main points made during the session.

3.1.2.1 What do we define as an advanced material?. The participants recognised that a definition for AM is necessary from a practical and regulatory perspective but nevertheless challenging. A definition would be useful for EHS regulations, for example, in helping to group AM for the purpose of toxicological 'read across'. However, it is not essential to have a definition to begin the required work related to AM.

The participants proposed that any definition of AM should include materials that are not currently used in existing systems. It was also thought that an AM is a material that offers new or improved properties, such as a composite, in relation to its increased performance. It was noted that, as discussed in the introduction, there is work underway at the international level to define the term advanced materials as well as other related terms. For example, ISO TC 229 in nanotechnologies are working on a definition for AM. Like their definition of nanomaterials,[29] this will be very much a 'dictionary definition' rather than a regulatory definition. The OECD has currently chosen not to define AM *per se* but has instead developed a working description.[10] Some countries, *e.g.* Germany[20] and the USA,[18] have identified specific groups of materials or technologies as 'advanced'.

3.1.2.2 Are AM eco-friendly and compliant with a circular economy based on safe and sustainable design?. Some participants answered that some AM may not currently be eco-friendly and may not be part of a circular economy due to a perceived current lack of appropriate recycling solutions or waste management approaches.

Fig. 2 Word cloud response to the question – *What are the barriers to create Advanced Materials that are both safe and sustainable by design?* (81 responses). Note that limited preprocessing of responses was undertaken prior to generating word clouds to group similar terms and harmonise.

To improve this situation, participants suggested that the following initiatives could be considered:

• Offering incentives to companies that utilise SSbD approaches.

• Incorporating SSbD practices into the regulatory framework.

• Educating companies about the importance of considering lifecycle issues.

• Educating consumers to create demand for sustainable products.

• Developing the skills of engineers in using SSbD tools.

To create safe and sustainable AM, the participants suggested developing effective partnerships between universities conducting research and companies implementing that research. Moreover, hubs could be established offering access to necessary infrastructure and guidance to support SMEs.

The participants recognised the importance of establishing standards and standardized procedures for AM that should include SSbD principles. They acknowledged that knowledge and guidance in existing measurement and test standards may apply to some AM with certain modifications. They also proposed that AM research proposals should be required to incorporate elements of SSbD to qualify for funding, in line with the EU funding policies for EHS research related to AM.

Additionally, the participants highlighted the need for more data to address the varying quality of existing information, particularly knowledge on the ecotoxicology and the fate of AMs during their degradation.

The authors note that the application of SSbD approaches is a high priority, nationally and internationally for all industries including AM, for example the EC Joint Research Centre (JRC) has recently published guidelines on SSbD.[30,31] Development of SSbD approaches and tools has been a focus for nanomaterials for some time.[32] Recent developments have provided greater focus on the application of SSbD to AM. For example, the OECD has recently advocated the application of a Safe and Sustainable Innovation Approach (SSIA) to nano-enabled and other emerging materials and recommends innovators integrate safety and sustainability considerations as early as possible into the innovation process.[11] SSIA, in this context, represents a combination of SSbD and the concept of regulatory preparedness, which aims to improve the readiness of regulators, to facilitate the development of adaptable (safety and sustainability) regulations that can keep up with material innovations (nanomaterials, nano-enabled products, and advanced materials). The EC has funded several Horizon 2020 projects applying the concepts of SSbD to nanotechnologies and AM. In 2022 a stakeholder's meeting involving representatives from the majority of these projects was held to identify differences and overlaps between the SSbD approaches being used and to reflect on progress and challenges to their implementation.[17]

The authors highlight that existing recycling infrastructure and general management approaches are generally applicable to AM and we can learn from past studies on nanomaterials where a CEN standard has been developed on waste[33] and also on lifecycle assessment.[34] Indeed, nanomaterials are recycled using infrastructure originally designed for non-nanoscale materials. Disposal routes for non-nanoscale materials are well defined and appropriately regulated in the UK as well as across all EU member states through national and the EU directives. UK and EU regulatory frameworks prescribe the appropriate waste treatment procedure depending on the classification of waste as hazardous or non-hazardous. The waste classification, which determines the appropriate pre-treatment and disposal route, depends on the hazard assessment and waste characteristics. It can also be expected, that only some AM will be classified as hazardous, which is similar to the situation for nanomaterials.

A key challenge that requires further discussion is the lack of appropriate measurement and test infrastructure to support establishment of a circular economy and the practical implementation and enforcement of regulations. The authors note that prenormative international interlaboratory studies, such as those developed by VAMAS (**https://www.vamas.org**) to validate and assess protocols are very beneficial. VAMAS is an international intergovernmental organisation that aims to accelerate innovation and trade of advanced materials by developing best practice and harmonisation, and accelerating standardisation.

3.1.2.3 What are the barriers and benefits to commercialisation of AM to contribute to a net-zero economy?. The participants identified that safety regulations are critical for industries working with AM, but some participants considered that aspects of the UK's industrial structure may cause challenges in meeting regulatory requirements leading to decreased innovation. For example, SMEs may lack the expertise and experienced staff to navigate regulatory requirements without support.

The participants suggested that there is a lack of comprehension within some parts of the industry regarding the potential advantages of AM and companies that have been successful in selling conventional materials may be hesitant to embrace change. This includes the inherent value of AM and how they may be integrated with existing technologies and used across multiple industries. Potential resistance from customers to adopt AM, based on mistrust in the safety of AM technology, may also act as a hindrance. The participants highlighted the lack of available exposure and hazard data for AM, and companies may therefore be hesitant to invest in these materials due to uncertainties surrounding their human and environmental toxicity. To address this issue, several solutions were suggested and included:

• Creating more efficient innovation and funding cycles involving multiple stakeholders,

• Improving communication between diverse groups involved in AM,

• Promoting knowledge transfer from academia to industry at the initial stages of development,

• Encouraging simultaneous testing for EHS aspects to minimise redundancy of tests, and

• Addressing infrastructure challenges to foster collaboration between academic research and industry.

The participants also acknowledged that the introduction of AM with enhanced performance has numerous benefits. These include the potential for reducing material and energy consumption, developing lighter and stronger materials, and creating competitive materials. Additionally, the adoption of AM can stimulate innovation and enhance the global reputation of the UK.

The authors emphasise the importance of knowledge transfer, collaboration and communications between all stakeholders including industry, regulators, governmental scientists, national measurement institutes, standards bodies and academia. This can be done for example through shared research programmes such as those funded by Innovate UK[35] or those initiated by HSE and industry.[36] Establishment of industry guidance with input from government departments could be a useful outcome of such collaborations, as, for example, the development of guidance on working safely with nanomaterials by the UK NanoSafety Group.[37] In addition, SMEs often lack the skills and infrastructure to run EHS testing, here collaboration with test houses and contract research organisations that can provide these services should be encouraged.

3.1.3 Final group exercise. The final session in Workshop 1 explored ways to continue and develop this 'conversation' on AM development. Two questions were posed, and responses collected using the online polling tool AhaSlides (**https://www.ahaslides.com**). They addressed potential topics for a future meeting (Fig. S4†) and approaches to information exchange (Fig. S5†). A range of topics was suggested including, material sector specific (*e.g.* polymers, energy materials and graphene) and more general subjects including tools and case studies, with regulation being the most popular by a small margin. Case studies were a popular response to the question on future information exchange as were further workshops, but a (knowledge) 'hub' received the greatest support.

3.2 Second workshop

3.2.1 Break-out discussion sessions. Participants were asked three multi-part questions as listed in full in section 2.2. Participants and author responses to these questions are summarised below.

3.2.1.1 What are the main obstacles to developing AM and could more support be offered to overcome these?. When considering or developing new AM, the participants identified several critical obstacles. These included the complexity of navigating regulations and the existence of different international regulatory frameworks. For SMEs, navigating the regulatory landscape and identifying the relevant standards can be challenging. Therefore, providing regulatory training will help them overcome this hurdle.

The participants felt that there is limited EHS information available for new materials (which is typically the case for novel or new materials), and that some test methods would require significant research and development. They believed that this reflects a lack of investment. Sharing data among stakeholders could improve data collection, and creating a sharing data platform could foster innovation. While large corporations may have the resources to form consortia to jointly contribute to data collection and its costs, SMEs may be unable to participate in these initiatives. Some participants considered that the cost and availability of *e.g.*, toxicological or materials testing services, is a significant barrier, especially for SMEs. Participants proposed having funded programs supporting national research communities to facilitate knowledge exchange about SSbD and the solutions to the challenges faced by these businesses. They suggested real case studies which illustrate the challenges faced by the industry in bringing AM products to the market could be made available to academia as training material for students. Academia could provide support to companies on scientific methodologies for SSbD and the approaches to effectively address environmental and health risks.

The participants mentioned national security considerations, such as those addressed in the UK National Security and Investment Act 2021 (Notifiable Acquisition) (Specification of Qualifying Entities) Regulations 2021,[38] may also apply to certain AM. Certain businesses have legal requirements when outsourcing substances or materials and this can be challenging when countries experience disruption in their supply chain. The participants also identified the scalability of materials as a potential barrier to developing new materials. Methods for small-scale production may not be transferable to large-scale production and up scalability should ideally be considered from the very start of product development.

The authors note concerns regarding the potential lack of detailed EHS information for some AM and questions regarding the applicability of chemical safety tests for some of these materials. This was an issue previously raised in relation to nanomaterials with many commentators noting that it was not feasible to provide data for all materials and that efforts focussed on "read across" and grouping were important in this context.[39] We note that the OECD guidance on Grouping of Chemicals[40] is currently being updated including the sections dealing with nanomaterials, which may benefit the field. In relation to the applicability of tests (*e.g.* OECD Test Guidelines) reviews have been undertaken on the relevance of OECD test guidelines to nanomaterials and gaps which might provide a useful template approach for the wider AM family.[41,42]

Given the wide range of AM, the authors believe that the prioritisation of research activities is an important factor. This relates to questions regarding, for example, which AM are in or close to commercial production, and which have the greatest potential for impact on human and environmental health and sustainability. This is clearly an important issue and the OECD Early Awareness and Action System for Advanced Materials (Early4AdMa), which has recently been published,[43] is pertinent. This is a systematic approach intended to "identify and describe potential safety, sustainability and regulatory issues of advanced materials at an early stage of their development or use", which was adapted from a system developed by authorities in The Netherlands and Germany. The outcome of the approach is intended to inform regulatory decision makers, policymakers, risk assessors, and regulators and could facilitate regulatory preparedness and making timely decisions to avoid or reduce safety and/or sustainability impacts. As such, the Early4AdMa is considered as a pre-regulatory and anticipatory risk governance tool.

3.2.1.2 How do you apply the concept of safety by design to AM and are there useful tools and support to encourage more use of SSbD?. The participants stressed the importance of engaging early with regulatory bodies. However, these bodies need the resources to impartially support companies before their AM products enter the market.

The participants highlighted it was important for manufacturers to consider the supply chain of raw materials and the life cycle of their products, including their composition and potential risk to the environment and human health. However, a holistic perspective is necessary to strike a balance between toxicological and environmental risks. For instance, the use of certain natural raw materials may have a detrimental environmental impact but may pose fewer toxicological risks. The authors note that the international standards committees ISO/TC 298, ISO/TC 345 and ISP/PC 348 are all looking at supply chains of critical, rare and sustainable minerals and metals. Sustainability being built into research and development stages from the very beginning could be a useful mechanism to ensure sustainability is considered from the onset.

The participants thought SMEs with limited resources could potentially access large industry consortia projects in which regulatory-approved toxicology tests can be undertaken at a lower cost through data-sharing agreements. Significant funding is available at the EU level for the development of SSbD approaches, allowing companies the prospect of implementing these approaches. However, it was noted by participants that companies may struggle to understand the relevant advice to bring their AM to the market because of the technical language used in these tools. The authors note that SSbD approaches are an increasing international focus and more guidance on their application is being developed. For example, the OECD Working Party on Manufactured Nanomaterials (WPMN) has subgroups on Advanced Materials and Sustainable Innovation and has recently provided guidance on a Safe(r) and Sustainable Innovation Approach (SSIA) for nano-enabled and emerging materials, which includes elements of SSbD.[11] They note that there is a need for a change of mindset to ensure that newly developed materials combine safety and sustainability from the innovation phase. SSIA proposes a systematic and comprehensive approach that considers sustainability aspects hand in hand with safety considerations early on in the material design stage. SSIA has the advantage that it also considers the relevant regulatory issues. The UK is active at WPMN and contributes to activities on AM and SSIA.

The authors highlight that the EC JRC has also recently published guidance on SSbD and AM specific guidance is also being produced by various EU Horizon 2020 projects (*e.g.* SUNSHINE[44] and HARMLESS[45]). Work has recently begun in CEN TC 352 (European nanotechnologies standardisation) on are developing a European technical specification on safe-by-design, which will be focused on nanomaterials and products containing them.

3.2.1.3 What do you foresee, or do you face environmental, health and safety obstacles when considering the end-of-life, of new AM?. When considering the end-of-life of new AM, several obstacles were identified by participants. In no particular priority order, these included the limited available information, test methods, and data on new AM, although participants did acknowledge that significant international work is being developed in these areas for simpler materials. Challenges in evaluating the end-of-life impact of AM and accessing support and funding were also highlighted.

Currently, the industry may not sufficiently focus on the end-of-life aspect of AM and could benefit from data, results and experimental methods to better understand their product early in its development. This includes evidence about the risks of harmful exposure to humans and the environment, and the tools required for conducting life-cycle assessments.

It was mentioned by the participants that companies should consider implementing recycling programs because they have a deep understanding of their products and can tailor the recycling process to fit their specific needs. Additionally, it is important to prioritise SSbD as regulations may have evolved by the time a product reaches the end of its life cycle. Long-term clarity is crucial for companies to develop new products, particularly when end-users express a desire to minimize the use of potentially harmful chemical substances. Efforts aimed at aligning the perspectives of various stakeholders would prove beneficial.

3.3 Summary and discussion

The workshops proved very useful in identifying the concerns of industry and researchers in the UK working to develop and produce AM and providing a forum for discussions with all parties (government bodies, research, measurement and standardisation organisations, academia and industry) on what they felt would help support them in their aims of developing innovative, commercially successful, safe and sustainable AM. The main conclusions, including issues, obstacles and potential solutions identified by the participants were:

- **Benefits and Opportunities:** participants highlighted that the introduction of AM with enhanced performance has numerous benefits. These include the potential for reducing material and energy consumption, developing lighter and stronger materials, and creating competitive materials thus helping stimulate innovation and enhancing the global reputation of the UK.
- **Definitions and standards:** developing AM definitions is challenging but necessary from a practical and regulatory perspective. Ongoing international activities in this area are appreciated, however it is not essential to have established definitions before commencing the required work on AM. Appropriate standards that are required include those on SSbD and on measurement and characterisation for individual AMs or groups/classes of AMs, as it is likely requirements will be very material specific. It was thought that many standards should be developed or adapted from existing standards.
- **Regulation:** EHS regulations are critical for the industries working with AM, but it was identified that SMEs may lack the resources to navigate these regulations without support. Perceived obstacles to the wider uptake of AM included the complexity of existing chemical hazard regulations, and the existence of different international regulatory frameworks, again this was felt to be especially challenging for SMEs. Education and training and promoting early communication between industry and regulators may assist in this area.
- **EHS:** information to allow appropriate risk assessments may be lacking for some AM and this uncertainty may make companies hesitant to adopt AM. SSbD approaches will play an important role in this area. The participants noted the work is being undertaken, particularly in the EU, to address these EHS data gaps. To encourage production of the required information a number of solutions were proposed, including that AM research proposals should be required to address EHS and incorporate elements of SSbD to qualify for funding.
- **Sustainability:** participants considered that work was needed to develop suitable recycling and waste management strategies for AM at the end of their lifespan, to ensure that AM are eco-friendly and will contribute to a circular economy. Long-term environmental impact of certain processes and materials are still not fully understood, this uncertainty adds to the risks for product developers. SSbD approaches could

play an important role in this context. Possible actions suggested by participants to address this included offering incentives, educating companies and consumers, and focussing on skills development in the AM workforce. SSbD tools are available but training in their application, perhaps using case studies, may be helpful, especially for SMEs. It was also suggested that companies should consider implementing recycling programs and prioritize SSbD principles at an early stage of product development as these regulations may evolve by the time their product reaches the end of its life cycle.

• **Finance:** it was considered that selective funding could assist in all areas identified. It was also noted that the cost and availability of toxicology and materials testing services can be a challenge for industry, especially SMEs.

• **Information, Education and Skills:** in addition to the education and training identified above, providing information to consumers and the wider industry may be useful. For example, concerns about their customers' perspectives on the risks of using AM technology may deter traditional manufacturing companies from adopting AM, which could be addressed by consumer focussed information. Participants also suggested that there is a lack of comprehension within industry more generally regarding the potential advantages of AM, and companies that have been successful in selling conventional materials may be hesitant to embrace AM. Information on the inherent value of AM and how they can require downstream technology changes to integrate with existing technologies and used across multiple industries may help in this context. AM are not always a drop-in solution.

• **Co-operation:** developing effective partnerships between all AM relevant stakeholders was considered a priority to address the issues identified including up and down the value chain and others such as infrastructure challenges and efficient knowledge transfer (*e.g.* shared databases). Promoting early interactions between industry and regulators was considered especially important. Joint research programmes may prove useful in promoting co-operation and knowledge sharing. In addition to the typical approach of funding academic–industry interactions, joint research programmes should encourage participation of measurement laboratories and regulatory agencies across all stages of technology readiness levels.

Some of the issues identified by workshop participants in relation to the development and commercialisation of AM in the UK are consistent with findings from other national activities. For example, the responses from the UK Government call for evidence on AM[27] (86 contributions primarily from academia, industry (including SMEs) and trade bodies) were similar to the workshop participants in highlighting the following: (i) the wide potential benefits of AMs, especially opportunities related to Net Zero and decarbonisation; (ii) the importance of metrology, measurement protocols and standards, although with perhaps a greater focus on their importance for commercial success (*e.g.* 'lack of standardisation contributes to customer confusion and could delay the large-scale adoption of UK-developed materials', and '(standardisation) allows international customers to understand and have confidence in the British products entering the market'); (iii) the key need to address sustainability, with suggestions that greater linkages within supply chains could make developing circular options and effective recycling more viable, with some respondents proposing a national programme for the end of life of AM with potential commercial benefits arising from the reuse of waste materials; and, (iv) the importance of education and skills, especially to support AM development, identifying the need for a strong pipeline of talented materials engineers that could meet the needs of UK businesses and noting the challenge in maintaining a critical mass of skills in the discipline with low retainment being an issue. This final point reflects wider national conversations regarding the delivery of STEM (science, technology, engineering and mathematics) skills to support the economy.[46] There were, however, important differences between the responses to the call for evidence and the workshop outcomes. For example, the workshop participants had much to say on the EHS aspects of AMs and the associated regulatory needs, whereas there was little reference to these by call for evidence responders, who specifically commented on UK strengths in sectors around assessing the health and environmental impacts of materials. Both groups highlighted the need for appropriate funding, although this was a much greater focus in the call for evidence, with requirements for funding identified at all stages, from basic research to commercialisation. The workshop participants acknowledged these funding needs but also considered the costs of toxicity and testing services to address EHS, including regulatory requirements. These differences may be a result of differences in the backgrounds, expertise and interests of those involved but also reflects the different objectives of the two exercises, with the call for evidence structured around questions focussed on commercial interests. The call for evidence also sought to identify potential learning opportunities from other countries and companies, which was not attempted here.

Many of the issues highlighted by the workshop participants have also been reflected recently in work undertaken by the Henry Royce Institute (**https://www.royce.ac.uk**). As UK Research and Innovation's (UKRI) national institute for materials research and innovation, the Henry Royce Institute for Advanced Materials is seeking to establish a National Materials Innovation Strategy to be developed in partnership with the materials community.[47] As part of this process industry stakeholders were invited to identify priorities. Over 1200 individual responses were collected and categorised into 6 core themes related to specific material groups (*i.e.* energy materials, soft materials, biocompatible materials (health, life sciences & agriculture), structural materials, materials for surface enhancement & protection, and materials for electronics, telecoms, sensing & computing technologies) and 6 cross-over themes. Three of the cross-over themes identified relate directly to issues raised in the workshops: (a) sustainability & circular economy, (b) skills, and (c) policy, regulations & standards. In relation to skills they identified the need for specialist engineers, including bioengineers, and materials and chemical scientists but also the need for digital skills. However, the need for wider education related to AMs as highlighted in the workshops was not reflected here. As in the call for evidence responses, the standards and regulatory aspects were very focussed on standardisation for commercial advantage. In terms of safety, the main focus was on the advantages of new materials to improve safety rather than any clear reflection on the potential need to assess EHS aspects of new materials and there was no mention at this stage of SSbD. However, the overall process is at an early stage, and they are intending to establish expert groups to explore these issues further and to make recommendations in various areas including finance.

Overall, we consider the outputs from the workshops have usefully added to national activities on AM, with a developing consensus in many areas, and the focus of the workshops on safe and sustainable development has been a useful complement to other, more commercially focussed, stakeholder engagement. In particular, this work has shed light onto the specific needs and challenges of SMEs, which could be helpful to inform policy and support actions. This is also echoed to some extent in the recently published Henry Royce Institute Report,[47] which notes that innovation could be inhibited by limited access to test capabilities for SMEs.

Many of the workshop findings are also consistent with those from other countries and international bodies. The importance of education and skills to support AM development is reflected by many countries,[23,28] although there are limited examples of a stated need for wider education and skills as identified here.[21] Appropriate financing arrangements is also an important area identified by many as key to commercial success.[24] SSbD, sustainability and the needs of the circular economy are also key AM themes.[11,17,21,23] The need for appropriate regulatory requirements to address EHS concerns was not highlighted by many but was a strong theme of some EU activities.[16] Prioritising different types/classes of AM for potential EHS concerns and regulatory activities was seen as a key next step for some[43] but was not raised by the workshop participants. In contrast to our workshop, we found few references to specific needs of SMEs. However, it is important to note that this comparison with activities in other countries and international bodies is limited by the ready accessibility of relevant information, much of which relates to activities of many different Government Departments and other national bodies within each country.

Activities currently underway, especially at ISO and OECD (as highlighted earlier) will assist in addressing some of the issues identified by the workshop participants related to standardisation and toxicity testing and associated prioritisation and also developing SSdD concepts and applications, and the UK is actively involved in this work. At the national level consideration is being given to the further development of the knowledge sharing network to possibly include future workshops focussing on those AM that are a UK priority for production and use (*e.g.* Graphene).

4. Conclusion

The creation of the first UK AM knowledge sharing community in April 2021 served as a starting point to share views on the benefits of advanced materials; including the societal benefits that may arise from this and the potential obstacles to the wider adoption of advanced materials. The first meeting included perspectives from organisations developing advanced materials, businesses manufacturing and using advanced materials, academics and regulators. The second meeting in February 2023 built on the first and focused on safety by design and life cycle analysis and included perspectives of challenges faced from different points in the supply chain. The key conclusions from these workshops support findings from previous national and international studies, but also shine light into specific challenges of SMEs that can help identify new actions and policies. The main points raised included: the need for sharing information (about benefits, opportunities and risks of AM, existing and upcoming regulations, finance opportunities, *etc.*), training and skills development (including on risk assessment and sustainability approaches), the importance and challenges of developing measurement and test standards, as well as finance and co-operation opportunities bringing together a diverse range of stakeholders. The findings will be used in future activities to facilitate the safe and sustainable development of AM in the UK.

Disclaimer

The contents of this paper, including any opinions and/or conclusions expressed, are those of the author(s) alone and do not necessarily reflect the views or policies of HSE, Defra, NPL, UKHSA, DHSC, DBT, DSIT and BSI.

Data availability

The data supporting this article have been included as part of the ESI.†

Conflicts of interest

There are no conflicts of interest to declare.

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