EXETER TECHNOLOGIES GROUP

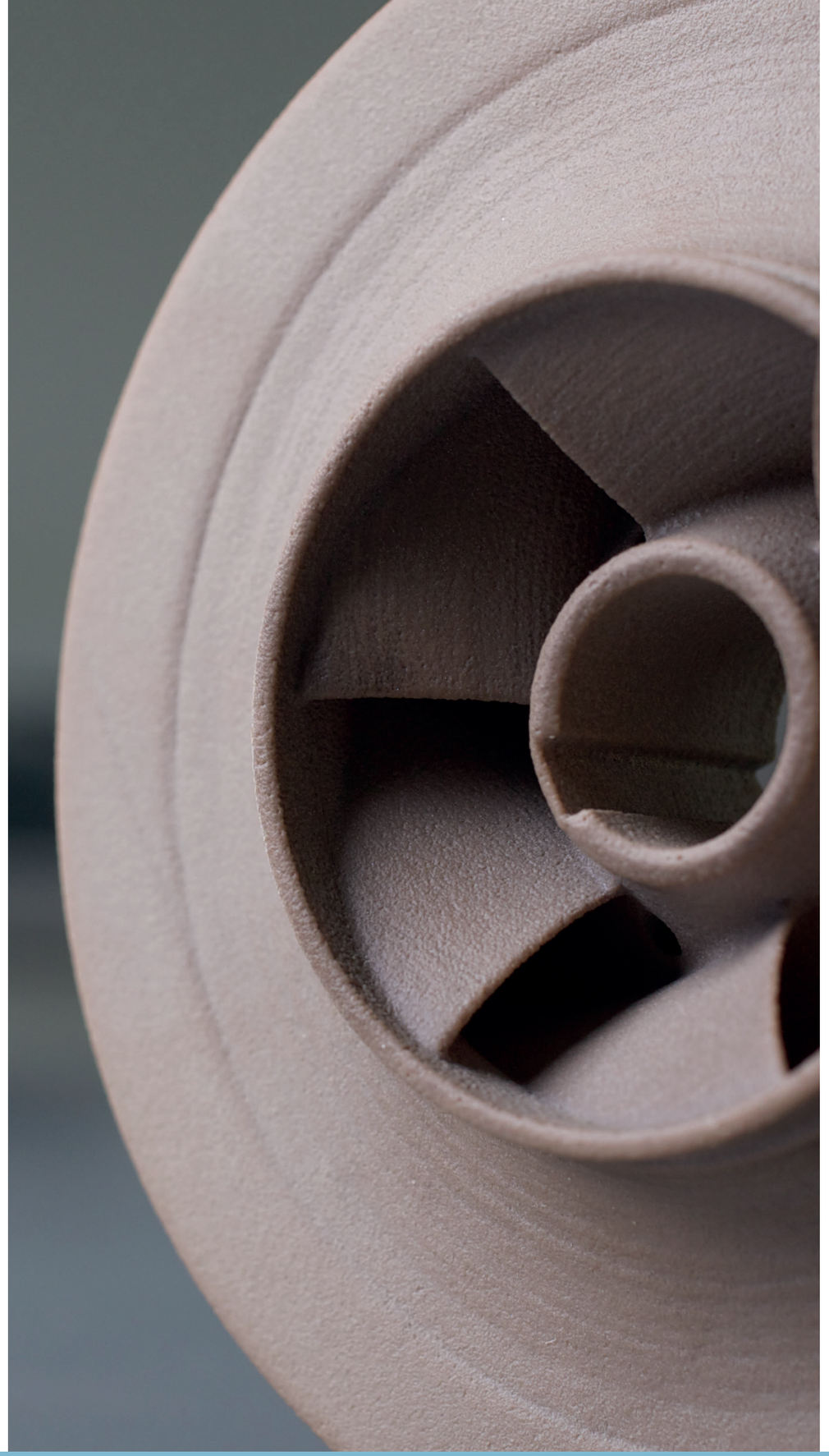
Centre for Additive Layer Manufacturing

ADDITIVE MANUFACTURING

High Performance Polymers Strategy
2018 – 2023

UNIVERSITY OF EXETER

contents



Strategic Vision and CALM's role

The Vision

Through collaborations and discussions with key industry partners, the Centre for Additive Layer Manufacturing (CALM) has developed a vision for the High Performance Polymer (HPP) sector of the Additive Manufacturing industry.

The aim is to transform the use of HPPs within the Additive Manufacturing (AM) industry, through coordinated R&D across the UK and Europe, to turn it into a high value manufacturing technology for the production of parts.

Together with support from industrial partners within the UK and EU, CALM is directing the development of robust materials and manufacturing solutions that offer guaranteed performance levels, whilst also supporting industry to bring them to commercialisation.

This report brings together the latest findings from industry forums to highlight the strategic direction required for the period 2018 – 2023.

CALM Overview

Established in 2010, CALM is a leading independent research centre, working at multiple Technology Readiness Levels, on both fundamental and applied research, with a focus on the development of advanced HPP materials for AM.

In recent years, CALM has taken a central role in coordinating UK and European AM activities for HPPs with a particular focus on high temperature. This has included hosting a biennial event – the European Strategy for AM with High Performance Polymers and its associated forum.

The outputs of these events have formed the focus of its continuing research and culminating in the clear strategic direction, required for the sector, detailed in this report.

For this next phase of work, CALM's intention is to build on this leadership role, working with industry partners to help deliver the objectives of this European Strategy, as well as providing new research and exploring potential areas of innovation.

Current HPP Market

For many years polymeric AM has had a limited number of commercially available polymers. However, in this rapidly evolving sector, there has recently been a significant push towards the use of high performance polymers (HPPs), with a particular focus on PAEKs (Poly Aryl Ether Ketones).

Known to compete in performance with metals, PAEKs are materials which can have a continuous operating temperature higher than 250°C in air. Transforming the landscape of materials usage, these materials offer far more than just lightweight replacements for metals, PAEKs are also resistant to ionising radiation, corrosion, abrasion and stress-fatigue, have low toxicity, and very importantly they are mechanically tough.

Development of these advanced high performance polymer materials for AM is now moving from prototype to large scale production methods for high value applications. Currently, this is a buoyant industry with a growing number of technologies and businesses appearing in the HPP AM market. At the time of writing, the Fused Filament Fabrication (FFF) market alone has over 15 printer manufacturers worldwide claiming the use of high temperature polymers, with many making reference to PEEK, PEKK and PPS. Unfortunately, the market lacks data and robustness for the technologies (printers) developed and is therefore difficult to evaluate, compare and recommend. Table 1 gives the name of a selection of HPP AM equipment manufacturers and material suppliers.

Amongst existing technologies, powder bed systems are closer to achieving large-scale production. The key players in the powder bed technologies are EOS GmbH and LSS Laser-Sinter-Service GmbH. EOS has a longer history in manufacturing high temperature polymeric laser sintering systems, whilst LSS is newer to the market and its high temperature system is based on the ThermoMELT process – technology patented by Airbus[1].

Other businesses such as BOND 3D and Impossible Objects have adopted different technologies from traditional FFF or powder bed process and are emerging industry players.

1. www.lss-europe.com/en/news/news/press-release-lss-laser-sinter-service-launches-raptor-series-the-most-productive-3d-printer-for-i/?tx_news_pi1%5Bcontroller%5D=News&tx_news_pi1%5Baction%5D=detail&cHash=2dadf6547bcfbb7958cf5201804ec9e7

AM with High Performance Polymers – Equipment and Material Manufacturers

The equipment and materials landscape is constantly evolving, but as a snapshot at the time of writing a collection of known companies offering equipment, claiming to be compatible with HPPs, are provided in table 1, with information about commercially available HPP materials for AM in table 2.

Table One – A selection of AM equipment providers for HPPs

Company	Type	Material	Company	Type	Material
EOS	Powder Printer	HP3 PEK, HT23 PEKK Carbon Fibre (23%), PEKK	**3DGence**	Filament Printer	PEEK
LSS (Raptor)	Powder Printer	PEKK	**Vshaper**	Filament Printer	PEEK
Stratasys Fortus	Filament Printer	Antero PEKK, Ultem 9085	**Rokit 3Dison AEP**	Filament Printer	PEEK, Ultem
Intamsys	Filament Printer	PEEK, PEKK, Ultem	**Dynamical systems**	Filament Printer	PEEK, Ultem (available 2019)
Apium	Filament Printer	PEEK, PEEK-CF, PEKK, Ultem 9085	**Innovo3D**	Filament Printer	PEEK, Ultem
Gewo 3D	Filament Printer	PEEK, PPSU, PSU, Ultem 9085+1000	**Kumovis**	Filament Printer	PEEK (claimed)
Roboze	Filament Printer	L+V PEEK, PEEK-CF, Ultem 9085	**Hage3D**	Filament Printer	PEEK, PPSU
Tractus	Filament Printer	PEEK, Ultem	**Creatbot**	Filament Printer	PEEK, PPSU
MiniFactory	Filament Printer	PEEK, PEKK, Ultem 9085, Ultem 1010, PPSU	**i3D Innovation**	Filament Printer	PEEK, Ultem
Aon3D	Filament Printer	PEEK, Ultem	**OO-KUMA**	Filament Printer	PEEK, Ultem
Hyrel 3D	Filament Printer	PEEK (claimed)	**Impossible Objects**	Laminate Printer	PEEK composites
nScrypt	Filament Printer	PEEK (claimed)	**BOND 3D**	Printer	PEEK

Table Two – High Perfomance Polymer Manufacturers/Suppliers

Company	Form	Material	Company	Form	Material
Solvay	Filament	Radel PPSU, Ketaspire PEEK	**Lehvoss Group**	Pellet (powder options include PP and TPU)	PEEK, PEKK, PPS, PEI, PA (high temp). Reinforcements: carbon, glass, ceramics spheres, CNT
Arkema	Powder	Kepstan PEKK (announced)	**3DXTech**	Filament	PEEK, PEKK, PPS, PPSF, Ultem, ESD-PEKK
Sabic	Filament	Ultem 9085	**Victrex**	Filament/ Powder	PEEK
Evonik	Filament	Vestakeep PEEK	**Ensinger**	Filament	PEEK, PPSU, PES,PEI, PVDF

European Strategy – High Performance Polymers for Additive Manufacturing

Overview and History

CALM, together with industrial collaborators, has been driving this niche sector forward with key innovations in material developments, methodologies and properties. Although HPPs have clear applications when used in conventional manufacturing processes, their use with AM processes requires re-evaluation from design all the way through to applications. In order for the high performance AM market to succeed there is a need for the technology push achieved so far to run in parallel with the market pull.

For this reason, CALM took the lead to host biennial international networking events, for the industry supply chain working within the High Performance Polymers sector, including material suppliers, machine manufacturers and end users from the UK and Europe.

These events provide industrial presentations, round table sessions and networking opportunities in order to share recent developments and identify the challenges still facing the industry. Through these events, a High Performance Polymer AM forum has been formed, numerous recent projects carried out and discussions held that have led to the development of this strategic report.

Biennial HPP Conference Outcomes

2014 Outcomes

Research findings presented in 2014 and the challenges inhibiting industry mainstream adoption that were discussed included a lack of process-specific high temperature materials, a need for enhanced recycling rates and lower overall production costs as well as more information about material properties.

2016 Outcomes

The second event, in 2016, highlighted a different set of requirements for the evolving industry with 'tailored' new materials now being developed. Robustness of the AM process was one of the major technical challenges still facing AM PAEK parts manufacture. There were concerns around the variability of the process and quality of end product to meet the lightweight, stiffness, flammability and chemical resistance requirements for aerospace applications.

Further research capturing data, more long term performance testing and the potential for real time process monitoring leading to a closed loop manufacturing process were identified as essential next steps. The use of nanomaterials with high aspect ratio, such as graphene and carbon nanotubes was also opening up new applications. End users were particularly interested in the long-term chemical, thermal and ageing properties of high temperature AM components.

The lower mechanical performance in z direction (high anisotropy) of AM parts was another area identified as needing more research to create the ultimate isotropic structures.

The highlights and results of the previous events from 2014[2] and 2016[3] can be found in recent editions of Aerospace Manufacturing magazine.

2. www.aero-mag.com/material-advances-dictate-ams-future/;
3. www.aero-mag.com/performance-polymers-performance-parts/

2018 Conference Headlines

2018 Event Overview

The 2018 event, which was part sponsored by Victrex plc, highlighted a clear evolution in priorities with the market players identifying a required shift from the fundamental material developments towards higher TRLs. This shows that the High Performance Polymer AM sector is moving in the right direction, with increased commitment from the involved businesses.

Attending the 2018 event were representatives from all across Europe (over 50% from outside of the UK) and from a wide cross sector of the industry including:

- Material manufacturers – companies from across the UK and Europe were among those attending and presenting, covering areas such as polymer chemistry and processing, composite materials and nano materials.
- System manufacturers – A wide cross section of system manufacturers attended including laser sintering and FFF based equipment providers along with parts suppliers from across the supply chain.

"This is now an essential event in our AM calendar. With its unique focus on High Performance Polymers, this conference is a great opportunity for Victrex to meet with AM users and to understand their materials requirements. We would like to see HPP AM included in the UK National AM Strategy"

Adam Chaplin,
Victrex plc

- Specialist AM service providers – The growth of the industry is reliant on being able to provide full end-to-end solutions and a wide spectra of the supply chain were present from milling companies, to post-processing specialists and companies providing bureaux and design services.

"We were impressed to see how Professor Ghita brings together many relevant parties and orchestrates the multi annual scientific roadmap driven from the round table discussions."

HenkJan van der Pol,
Bond High Performance 3D Technology

- End Users – Developing application specific solutions has been identified as critical across many areas of AM. It is also the case for HPPs with end users and OEMs commited to this journey with representatives at the event from Aviation, Defence, Bio-Pharma and other research organisations.

Strategic Directions Identified

Strategic areas identified for further research and development are highlighted below:

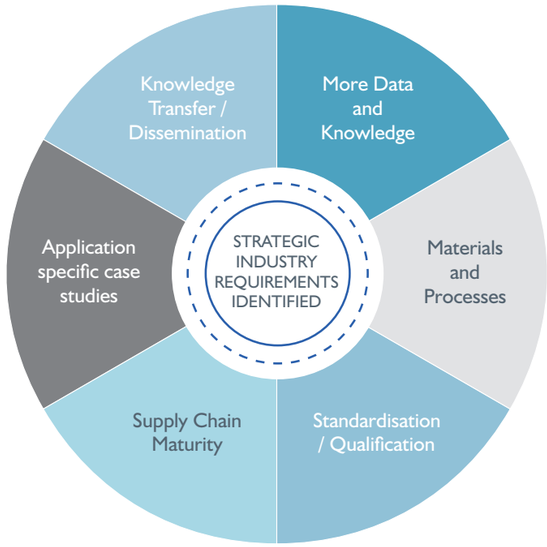


Figure 1 – Strategic Industry Requirements – key findings from 2018 event.

Strategic Industry Requirements Identified

More data and knowledge

More data is needed on existing materials to bring them to commercialisation. A focus on a small number of grades suitable for a large proportion of manufacturing needs is required.

End users clearly stated that there is a lack of data, design guidelines or materials and process specifications to allow them to take informed decisions and consider HPPs and AM for new applications. The Fused Filament Fabrication process is an example where a large number of printers became available; sometimes with unsupported material claims and sporadic data. It is predicted that the success of many of these combinations of material/FFF processes depends on making large data available to the rest of the industry.

If now the number of AM materials seems to be going up, satisfying the end users and manufacturers, the understanding of the long term behaviour and stability of the additively manufactured parts is still not known. Accelerated or long-term stability tests which are industry specific need to be carried out. Composite materials formulations and control of fibre/filler, (eg. carbon fibre), in relation with specific AM processes also has to be rigorously evaluated.

Materials and Processes

With considerable progress made in recent years on the development of new materials and processes, together with a deeper knowledge of the underlying material science, there is still a considerable amount of further R&D required to bring these solutions to market and to provide the levels of data required by end users.

In addition, work needs to continue on making materials and processes designed and optimised specifically for Additive Manufacturing. Areas identified include developing new processes of making high performance powders, as well as a robust understanding of them; continued development of the next generation of materials (eg. composite materials for multifunctionality) and ensuring that the intellectual property arrangements allow growth of the market and continued innovation.

Standardisation and Qualification

The event highlighted that the industry needs AM standards to be developed (eg. ASTM/ISO standards for each manufacturing process.) Robust characterisation methods, process consistency and compliance with standards remain an issue in AM.

The build and sample preparation for testing of Z tensile test specimens among the FFF printers was an obvious example noticed throughout the presentations with data provided on machined, polished or as-build test specimens.

Supply Chain Maturity

In recent years, one of the issues, which CALM has been focused on addressing, is the risk adversity of different aspects of the supply chain. This has been addressed through bringing the supply chain together for collaborative R&D projects, such as a recent Aerospace Technology Institute (ATI) project (High temperature, affordable polymer composites for AM aerospace applications) and various Innovate UK projects. This will be further enhanced as the HPP AM network is growing, accelerating the rate of R&D and uptake of the new materials and processes available. Involving compounders, milling processors, surface finish developers and bureaux is key to creating a sustainable and healthy supply chain. While the filament fabrication for FFF processes seems to be successfully covered by many compounders across UK and Europe, the milling processors are in high demand when it comes to powder bed processes.

Application specific case studies

Feedback from the presentation of any case studies has been excellent from all events held and it has been identified as a vital area for further market development with R&D needing to be 'tailored to specific applications.'

Aerospace, defence and medical have been identified as potential candidates for the development of new case studies, expanding on work done in the recent ATI project. This was carried out by a consortium of 7 partners, led by Victrex plc, and delivered the first two aerospace demonstrators (non-structural aircraft bracket and ducts) made of PEEK, through a powder bed process – see further outcomes in the Aerospace Manufacturing magazine[4]. However, there is a need for more demonstrators and a wider range of applications. Throughout the event it was concluded that identification of case studies also requires the involvement of bureaux and companies with expertise in design. This is important as the lack of AM design knowledge and design guidelines, or incorrect assumptions of what is suitable for additive manufacture, often leads to a breakdown in ideas and hinders the development of such case studies.

Knowledge Transfer

During the 2018 event, some of the mainstream manufacturers (with experience in metals and thermosets) expressed significant interest in polymeric AM but at the same time stated that there is little knowledge and information available to build up the confidence in thermoplastics AM in general. There is a need to educate and raise awareness among such companies familiar with thermosets and metals but lacking knowledge of HPPs – materials often considered metal replacements.

This lack of knowledge is common throughout the supply chain and in parallel with the data gathering a focused effort on knowledge transfer is required.

4. www.aero-mag.com/is-paek-am-now-a-reality

European Strategy – Our Recommendations

1. Formalisation of AM High Performance Polymer network

Expanding on the work carried out by CALM in establishing an informal European network, a strategy board should be created to include a small group of key representatives of industry and academia: material suppliers, equipment manufacturers and end-users willing to disseminate and promote the work happening in this AM area. The steering group and a more formalised network should coordinate activities to further develop knowledge, grow the sector and lobby the government in UK and the other countries, promoting this niche AM sector and securing funding. Investigation of funding mechanisms is required and a final structure needs to be determined including the potential of creating working groups.

2. Tackle the current technical challenges

With regards to current and new materials and processes, the network will continue to work collaboratively to overcome a number of identified areas that need further development, including the development of new materials and processes.

3. Data creation and data science

A key area highlighted by the network is the requirement for greater data; particularly for materials but also for processes and market information. There is also a need to connect the materials and manufacturing AM research with data science, engaging with the Alan Turing Institute in the UK and other similar centres throughout Europe.

a. Materials and process data – data should be developed to allow manufacturers to evaluate the technology and existing materials:

  i. Materials – Significant advancement has been made on new materials for the HPP sector. In order for these to be successfully commercialised, full testing needs to be carried out to produce sector specific databases to allow selection during the design process.

  ii. Process data – With the emergence of new players into the market and a plethora of new capabilities (particularly within Fused Filament Fabrication) a process of independent verification of these capabilities needs to be defined.

b. Data exchange – A framework should be set up for businesses to engage with, including incentives to make it more attractive to join. Frameworks should be application or sector specific with key businesses within the sector agreeing on terms and working collaboratively to deliver value to the market.

c. Development of standards – Clear standards for AM need to be developed. The network should coordinate with other groups investigating AM standards to ensure the specific requirements for HPPs and for any identified target applications are being considered.

4. Application and sector focussed R&D

In order to bridge the gap between current development (TRL1-4) and TRL (6-7) known as the valley of death, a number of initiatives need to be established. These could include:

a. Identification of target sectors and production of case studies, with technologies developed specifically for these applications. The network could be expanded to bring in new academic/research partners with more recent expertise in High Performance AM area. For example, focused specifically on the medical sector or oil and gas industry to help identify and develop these case studies.

b. Engagement with the government funded manufacturing centres to push the technology forward including the UK manufacturing catapult centres, the Fraunhofer institutes, Thermoplastics Composites Research Centre (TPRC) etc.

c. Establishment of regional business technology centres (BTCs) with a specific focus or theme, allowing specific academic research centres to partner with the catapult centres as part of these BTCs.

d. Development of data exchange frameworks for these sectors.

5. Training and upskilling

Engage all aspects of the supply chain through European wide brand campaigns and collaboration with other AM knowledge exchange initiatives. Aspects to investigate could include:

a. Provision of apprenticeship programmes and postgraduate programmes to upskill and reskill staff in AM technologies, including the existing bureau network and businesses already fronting up the technology who are looking to develop robust supply chains.

b. Using the application driven approach, and incorporating existing bureaus, identify potential components / applications and use these to train and develop approaches to AM including new design thinking and AM design guidelines.

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