AEROSPACE TECHNOLOGY INSTITUTE

AEROSPACE ALUMINIUM SHAPE CASTING ROADMAP

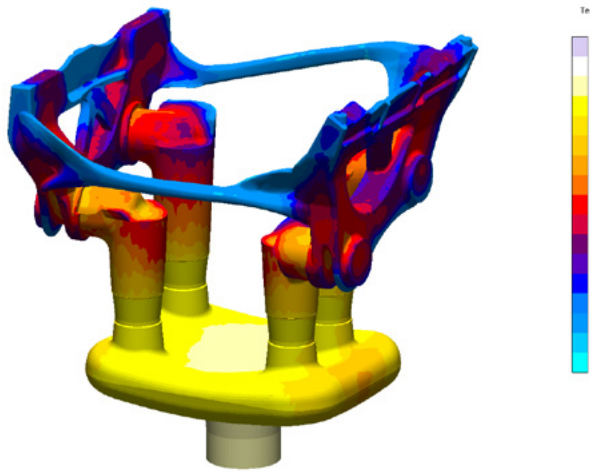
Foreword

Casting is a near net shape process that forms components with complex geometries by pouring molten metal alloys into shaped moulds, followed by careful cooling to solidify the metals. It is a traditional process, that has been used for 4000 years, evolving from an artisanal craft to a production process that provides engineered components for all sectors in a wide range of sizes and volumes.

As the aerospace industry has developed, continued focus on improving safety has resulted in formal procedures for the specification and characterisation of materials. Cast components have tended to be heavier and limited in scope of applicability as casting processes have yielded variability in the quality of cast components.

Future civil commercial aircraft, alongside emerging urban air mobility platforms, present an ever more challenging set of requirements in terms of cost, rate, weight, performance, component multi-functionality and sustainability. Casting offers a route to satisfy these requirements with commercially viable and competitive solutions, provided casting technologies are sufficiently evolved to give acceptable product quality. With a transition towards more sustainable manufacturing, metal castings, which are inherently recyclable, have a huge role to play in forming a sustainable circular economy around the manufacture of near-net-shaped components.

This roadmap identifies the aerospace opportunities for aluminium casting and outlines the key technologies required to realise them. Delivery of these technologies will benefit the whole aerospace sector, protecting and enabling the future growth of the UK aerospace casting industry. It is intended to initiate the development of a national casting technology strategy for aerospace that will provide clear direction, capture the process requirements and provide a guide for OEMs, designers and foundries as well as for academia and RTOs for future investment and technology innovation.



HVMC Sprint, Foundry 2030 project, low pressure die casting simulation of the selected aerospace structural component.

HVMC Sprint, Foundry 2030 project, rendering of aerospace the structural component chosen for the BCAST low pressure die cast part of the project.

CAST METALS FEDERATION

ALFED ALUMINIUM FEDERATION

Contributors

Dr John Forde

Following 12 years as a lead technologist in the aerospace foundry industry, John set up JFAdvancedTechnologySolutions in 2018 to support foundries in meeting the evolving technical, quality and performance requirements of casting end-users. This has evolved to include the broader ambition of facilitating a disruptive advancement in casting utilisation through optimised design for manufacture and full value chain technological & digital evolution. With a doctorate from the University of Birmingham, John has a background in aluminium alloy development & industrialisation, alongside extensive practical experience in alloy and foundry process optimisation.

Dr Mark Jones

Dr Mark Jones is currently Head of Business Development for BCAST and leads the development and delivery of large-scale strategic initiatives. Before being promoted into his current role, Mark managed the EPSRC £10m Future Liquid Metal Engineering Hub. Previously, Mark worked for KPMG as a Management Consultant across numerous diverse programmes, including aerospace, automotive, banking, and wider manufacturing. Mark also has extensive experience within the aerospace sector, while based at Airbus within their R&T manufacturing division, and has a PhD in Aerospace Technology Management, which received several awards.

Matthew Cawood

Matthew Cawood is currently Head of Group for Castings at the University of Sheffield's Advanced Manufacturing Research Centre. He has over 20 years' experience in the technical and quality aspects of castings production. Having gained an honours degree in Metallurgy, his practical experience has been built upon by working closely with the AMRC's aerospace partners over the last 8 years. This has enabled him to gain a detailed insight into the future direction of metal casting technology required by the aviation sector.

Alex Hickson

Alex is responsible for the ATI's work on aerostructures of the future, one of the key themes identified in the Institute's Technology Strategy. Innovative manufacturing methods and technologies, as well as new materials such as composites, are critical to ensuring the UK is a global leader in the development of large complex structures, particularly wings.

Alex joined the ATI in 2019, bringing experience from across various industries including aerospace, automotive, motorsport, wind energy and space. He has also worked across a breadth of companies, from start-ups and SMEs to blue chip companies including Lockheed Martin and GKN Aerospace.

Matthew Bailey

Matthew is a Senior Technologist at the ATI in the Structures, Materials & Manufacturing team. Primarily focussed on supporting metallic technologies including, but not limited to; castings, joining and subtractive processes. Before joining the ATI, Matthew worked at Airbus for nearly 10 years across several departments including Research & Technology and more recently Cost Engineering.

Introduction

Why is casting still relevant?

Aluminium shape casting can deliver cost effective, sustainable, complex, near-net-shape (NNS) components and can exploit developments in generative design to further increase design freedom and reduce component weight. In addition to lightweighting, improved casting quality can drive increased sustainability by extending the operational life of typical cast products. Aluminium casting has the potential to enable a circular economy in aluminium components for aerospace; current casting processes utilise up to 70% secondary material in new components. Full circularity would result in a 95% reduction in CO2 emissions relative to a manufacturing process that uses virgin material.

Historically, casting processes have given significant variability in the material properties of the resulting cast components, meaning that a 'casting factor' must be added to the design of cast components to account for this. Typically, this can mean that cast components can be 1.4 to 1.7 times heavier than components made through other processes and limits their scope in aerospace to less critical applications. Process simulation and technologies for improved process control have led to step-change improvements in the casting of other metals, such as single crystal nickel turbine blades. These approaches need to be applied to aluminium casting to reduce casting factors and enable a much broader applicability for cast components to fully realise the benefits of cast aluminium in aerospace.

What about additive manufacturing?

Additive manufacturing is often seen as a direct competitor to casting. It offers many comparable benefits, such as high levels of material efficiency and exceptional design freedom alongside the additional advantage of being an inherently digital process. Additive manufacturing and casting are both variable cooling rate processes with limited scope for thermo-mechanical post processing. This is important as many of the concerns associated with the further exploitation of casting in aerospace can also be applied to AM; namely the generation of and accessibility to accurate design allowables, potential manufacturing/post process variability and the cost and accuracy of post-production defect detection requirements. These challenges will need to be overcome for AM to be technically and commercially viable for widespread aerospace utilisation and to broaden the applicability of castings.

The reality is that additive manufacturing and casting should be viewed as highly complementary processes. This has already been demonstrated in industry. There is an opportunity for a synergistic approach to address the mutual challenges to exploitation for both AM and casting which should extend to a 'shared-platform' development of next generation alloys, digital material & process qualification capabilities and accelerated post-process automation and digitalisation. Such an approach could lead to a future where hybrid cast & metallic AM manufacturing processes can realise highly optimised components which utilise the best of both processes - adding material post casting to increase design complexity while simultaneously reducing tooling cost. Indirectly, AM-produced moulds and patterns are revolutionising shape casting by reducing lead times, increasing design freedom and process repeatability, and enabling process digitalisation.

The Trent XWB engine ICC is an advanced structural engine casing, a combination of titanium castings, forgings, sheet metal components and the latest laser metal deposition (LMD) techniques.

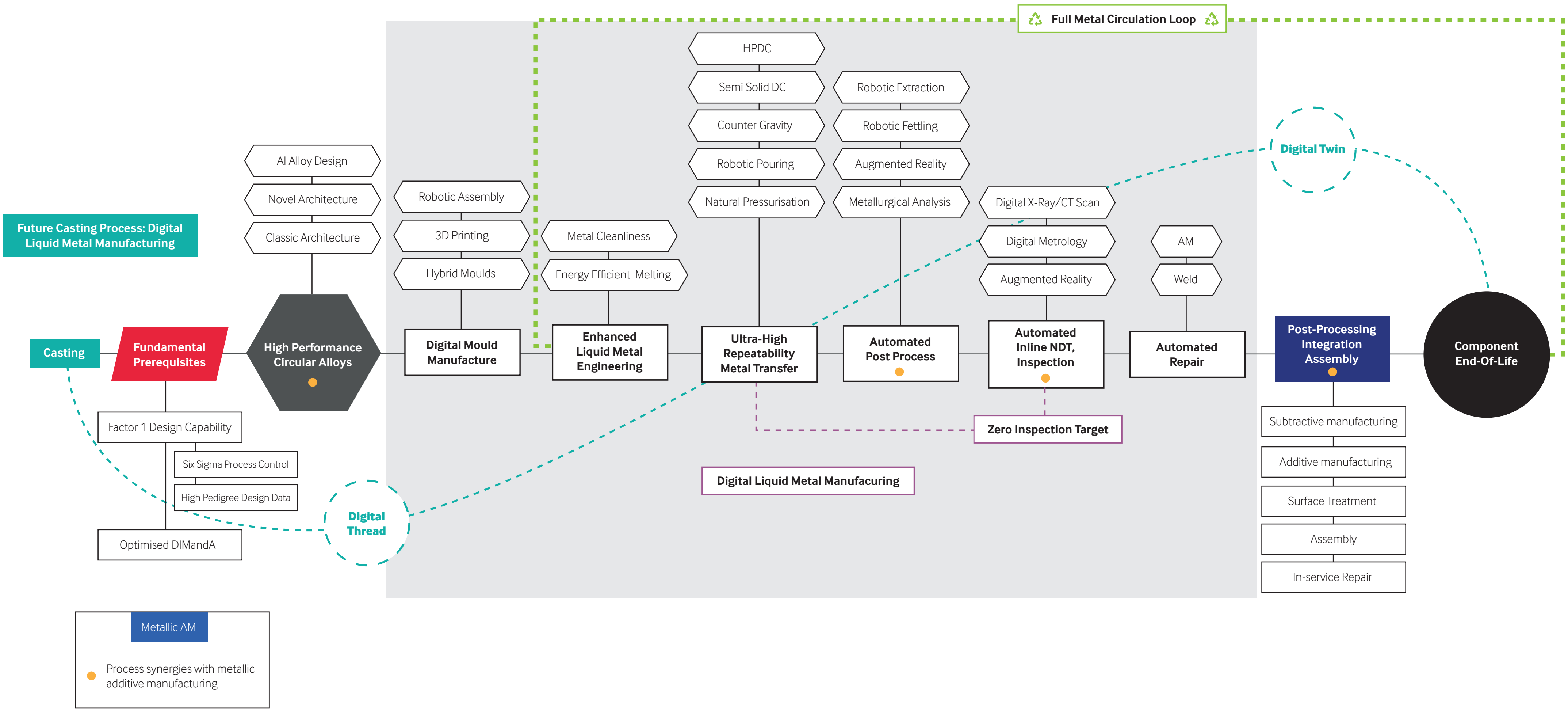
Image courtesy of GKN.

Rolls-Royce single crystal nickel turbine blades, an example of castings in highly loaded, critical applications.

Vision - Digital Liquid Metal Manufacturing (DLMM)

Digital Liquid Metal Manufacturing (DLMM) is a future vision for aluminium shape casting with a true end-to-end philosophy spanning manufacturing, assembly, operation and end-of-life.

The approach will support the manufacture of high complexity, cost effective, sustainable, high performance aluminium components within a fully digital, highly automated and robust ecosystem.

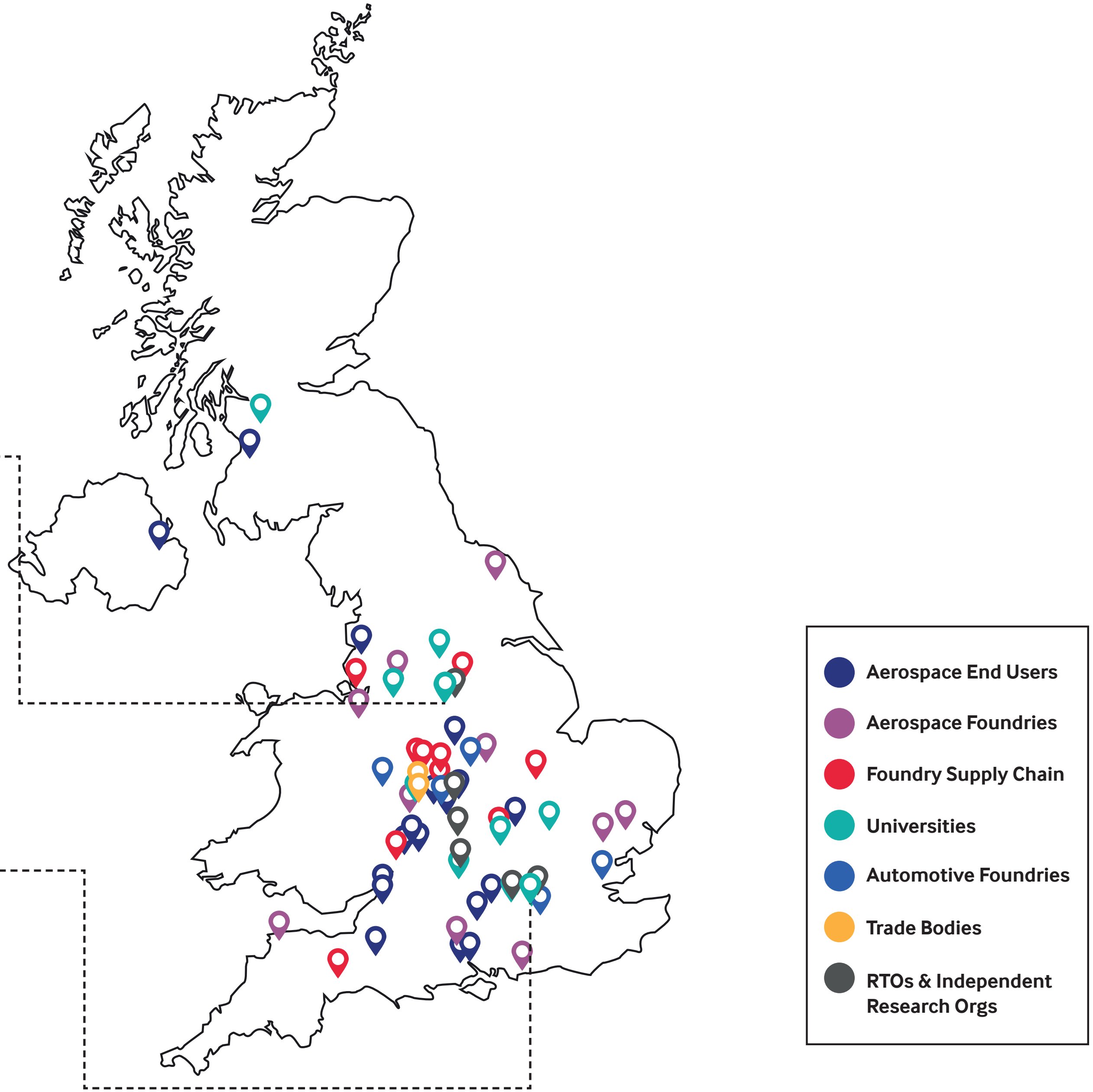


Ecosystem

The UK has the capability to become a world leader in digital aluminium shape casting through the exploitation of the existing, outstanding facilities, infrastructure and knowledge. The UK is well positioned with a strong academic capability covering fundamental research, a diverse foundry and enabling supply chain base and end-users in the form of both OEMs and leading Tier 1 suppliers.

The University Of Sheffield. AMRC Advanced Manufacturing Research Centre

Brunel University London BCAST



Roadmap Consultation

Consultation Process

The consultation for this roadmap took place between in the first half of 2020. Two webinars were held on the 30th April & 15th May 2020 attracting a broad participation of aerospace end-users, foundries, enablers, automotive companies, RTOs and trade organisations.

In parallel, more detailed discussions were held with a number of organisations and in addition a detailed survey covering the perceptions and challenges facing aerospace castings which was completed with five large aerospace end-users spanning aerostructures, propulsion and systems.

NB: The consultation was led by John Forde

JF Advanced Technology Solutions

Direct Consultation - Aerospace End Users

Five aerospace end users were selected for a further detailed direct consultation. The five companies spanned aerostructures, systems and propulsion.

Individual stakeholders interviewed and asked to rank importance of following casting development themes 1 to 5 (5 = most important, 1 = least important).

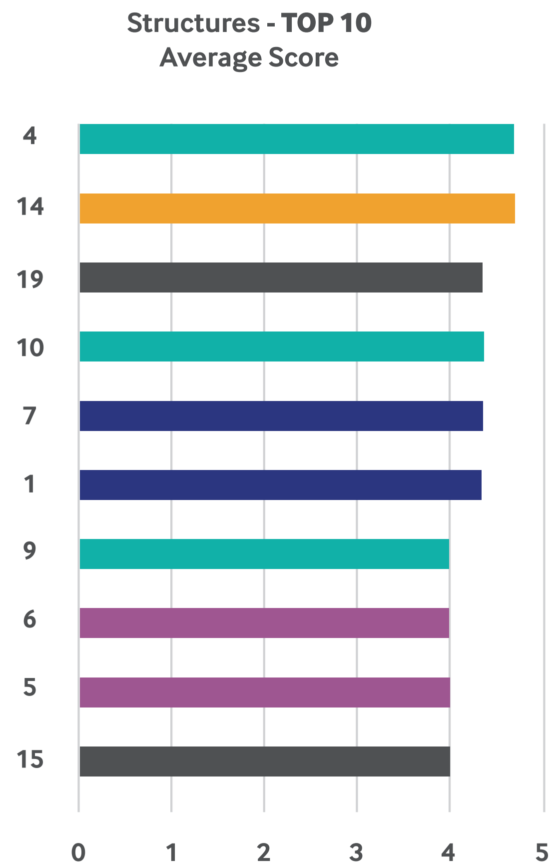
Industry Ethos Driven

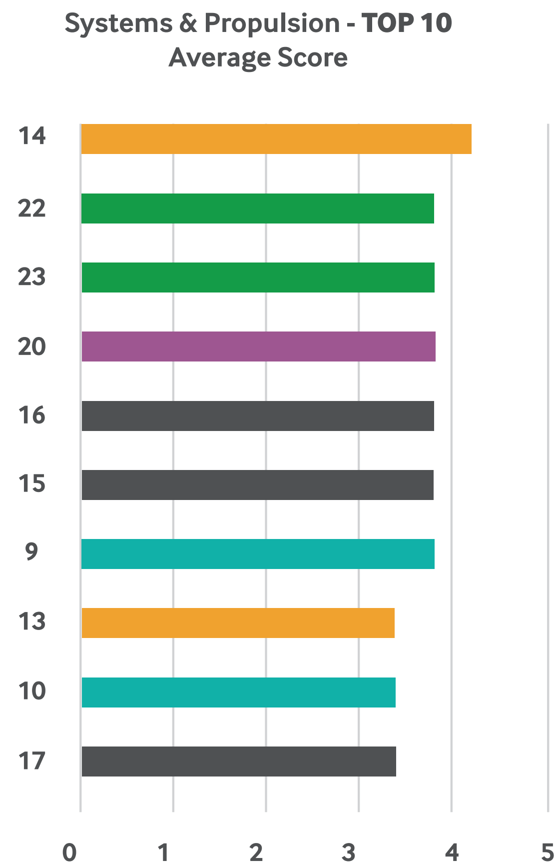
Approvals, Allowables & Specifications	1	Align next-gen cast and AM material specifications and allowables
	2	Review and streamline costly 'supply-chain' qualification/requalification procedures and M&P approval/reapproval processes
Design & Analysis	3	Provide design engineers with a casting process capability toolkit
	4	Eliminate casting knockdown factors
Supply Chain	5	Improve supply chain technical capability and transparency
	6	Increase supply chain engagement with academia

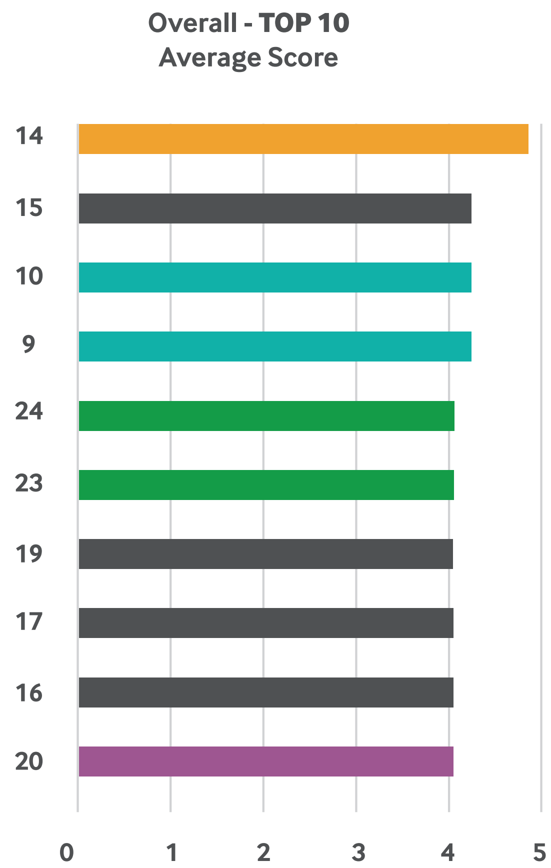
Technology Driven

Approvals, Allowables & Specifications	7	Recalibrate cast alloy specifications
	8	Introduce a microstructure based allowable systems
Design & Analysis	9	Increase DfM&A focus & generative design utilisation
	10	Improve casting process simulation accuracy
Materials	11	Optimise existing cast alloys
	12	Develop greater understanding of the impact of impurities on material performance
	13	Explore castability of existing non-casting alloys
	14	Develop new high strength / high temperature alloys
Manufacturing & Processes	15	Demonstrate current 'state of the art'
	16	Exploit existing and nascent casting process advancements
	17	Characterisation and adoption of cross-sectoral casting technologies
	18	Develop agile, modular, future-proof, digitised processes
	19	Development of integrated cast-additive-NNS manufacturing processes
Supply Chain	20	Enable Industry 4.0 readiness
	21	Develop and evolve turn-key processes for structural components
Technology & Cross Cutting Enablers	22	Continue and broaden application of additive manufacturing for mould and tooling development
	23	Microscopy, characterisation & NDT technology advancements
	24	Integration of proven & nascent automotive industry casting know-how & manufacturing capability
	25	Robotics & cobotics & automation

GKN AEROSPACE HAMBLE aerostructures an Aernnova company SPIRIT AEROSYSTEMS Rolls-Royce EATON







Generally there is a very close alignment between the aerostructures and systems/propulsion end users with development of new high strength / temperature alloys, increased DfM and generative design and process simulation improvements seen as priorities overall.

Notably, there were some interesting priority differences between aerostructures and systems/propulsion:

Allowables – the aerostructure stakeholders rely more heavily on classic manufacturing processes where there are well established and published allowables, as such they are more supportive of refinement and democratisation in this regard. Many non-structural casting users have built up extensive internal design data which they see as a competitive advantage.

Casting Factors – the requirement for the stringent application of casting factors applies only to structural castings; it is primarily in high-rate structural components where the additional weight is most detrimental, hence the greater push from aerostructures stakeholders for their removal.

Aluminium Shape Casting/[DLMM] Technology Roadmap

	2021-2025	2025-2030	2030-2035+
VISION	Casting alternative for high buy-to-fly components (machined, fabricated assemblies). Secure casting as primary next-gen manufacturing technology for propulsion & systems.	Casting as a potential primary manufacturing route for structural applications. Nascent DLMM solutions for conventional & alternative propulsion.	Fully, optimised circular, integrated & multi-functional DLMM structures, systems and sustainable propulsion.
KEY ENABLERS	Demonstrated repeatable and reliable process, optimising existing alloys and simulation capability.	Elimination of casting factors and transition to future process including greater automation, end-to-end simulation, micro-structure based allowables. Repeatable process and reduced/eliminated defects.	Full realisation of DLMM vision, fully automated processes with entire life digital thread. Use of hybrid AM-casting. Full metal circularity.

TECHNOLOGY FOCUS AREAS	
APPROVALS, ALLOWABLES & SPECIFICATIONS	Recalibration of specs & allowables for optimised alloys & processes → Develop process independent, microstructure-based allowable system to align Casting & AM and enable NNS process compatibility Redefine NDT inspection criteria → Reduce/eliminate casting factors through enhanced NDT, M&P control → Reduce/eliminate NDT through process optimisation & digital twin/thread capbility Review M&P & supplier approval processes → Develop [DLMM] based M&P virtual validation & approval framework → Full digital qualification platform for [DLMM] M&P's
DESIGN & ANALYSIS	Optimisation & refinement of existing casting simulation capability Increased 'co-design' to exploit inherent casting design for total life capability; refined allowables + process simulation + optimised design Develop open-source, refined, M&P boundary condition database to support design for total life → Enhanced M&P boundary condition accuracy through digital M&P validation and closed loop digital twin capbility Develop fully integrated [DLMM] focused design/simulation/validation platform to support full exploitation of optimised design for total life capability
MANUFACTURING & PROCESSES	Casting capability evolution through existing & nascent technology adoption → Reduce/eliminate defect related cosmetic weld repair Cross-sectoral knowledge transfer to accelerate advancements in automation, rate capability, repeatability and sustainability Characterise full value chain 'automation & digitisation' requirements → Development of [DLMM] IoT / digital twin / digital thread → Fully imbedded [DLMM] digital twin/digital thread capability Develop [DLMM] framework → [DLMM] evolution through existent & nascent technology integration & novel technology development → Fully automated, lights-out [DLMM] facilities Evaluation of [cast-metallicAM] process synergy → Develop hybrid [DLMM-metallicAM] processes for manufacturing & MRO → Hybrid [DLMM/metallicAM] manufacture & MRO processes
MATERIALS	Optimise and exploit extant alloy systems; enhanced performance, consistency & sustainability Development of 'aluminium aerospace foundry' circular economy framework → Cross sectoral integration to support full UK aluminium circularity Alloy evolution based on classic precipitation/solid solution architecture; enhanced manufacturing-process & application driven performance & increased circularity Novel alloy development for optimised [DLMM] processes; classic and novel architecture, fully circular, enhanced application driven performance, process independent AI driven alloy optimisation & development; conventional validation & approval with parallel digital validation → Fully digital alloy, development, validation and approval
	Today-2025 / 2025-2030 / 2030-2035+

Technology Focus Areas

1 APPROVALS, ALLOWABLES & SPECIFICATIONS

2 DESIGN & ANALYSIS

3 MANUFACTURING & PROCESSES

4 MATERIALS

1 Approvals, Allowables & Specifications

Expand and improve cast alloy design data, its interpretation and utilisation. Synergise cast alloy and additive manufacturing alloy microstructure based allowable systems for future interchangeability.

2 Design & Analysis

Improve Design-for-Manufacture utilisation and integration, with casting process simulation. Improve cast and post-cast process simulation accuracy and industrial utilisation. Reduce, then eliminate casting factors.

3 Manufacturing & Processes

Step change requirement in process consistency, reliability, rate capability and cost efficiency. Evolution of an agile, modular, future-proof, digitalised processes to support Industry 4.0 requirements. Development of an integrated, synergistic cast-additive manufacturing process.

4 Materials

Increase operational window of existing cast alloys. Development of ultra-high strength/high toughness castable alloys. Development of thermally stable alloys for elevated temperature applications and modular alloys, that are impurity tolerant to exploit potential process circularity.

Approvals, Allowables & Specifications

APPROVALS, ALLOWABLES & SPECIFICATIONS

1. Recalibration of specs & allowables for optimised alloys & processes → Develop process independent, microstructure-based allowable system to align Casting & AM and enable NNS process compatibility
2. Redefine NDT inspection criteria → Reduce/eliminate casting factors through enhanced NDT, M&P control → Reduce/eliminate NDT through process optimisation & digital twin/thread capbility
3. Review M&P & supplier approval processes → Develop [DLMM] based M&P virtual validation & approval framework → Full digital qualification platform for [DLMM] M&P's

DESIGN & ANALYSIS

MANUFACTURING & PROCESSES

MATERIALS

1 Specifications & Allowables

Re-define allowables based on current metallurgical understanding and move to an allowables system based on microstructural characterisation and casting quality. This approach will harmonise the performance of produced components resulting in increased consistency without the complication of process specific specification.

2 Inspection

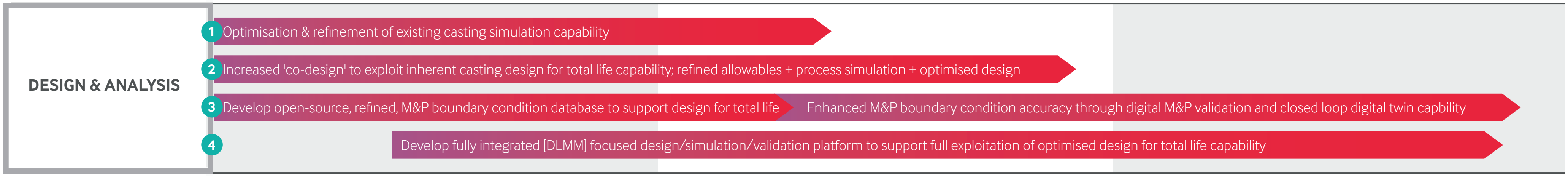
Increase the level of automation and Industry 4.0 technologies to predict and detect defects in real time during the manufacturing process. Such intelligent monitoring technologies will reduce the reliance on inspection for the detection of material flaws.

3 Supplier Approval Process

Generation of a unified approach to supplier approval. Approval will be generated from a process capability assessment and the calibration of real-world microstructures against the predictions from computer simulation. Such an approach would simplify the process and be driven by repeatability and predictability by demonstration on test pieces as opposed to each individual geometry.

Design & Analysis

APPROVALS, ALLOWABLES & SPECIFICATIONS



MANUFACTURING & PROCESSES

MATERIALS

1 Simulation

Optimise the methods of calibrating commercial simulation products with refined allowables and foundry specific facilities, processes and outcomes. This will help the generation of a digital twin of the casting facility to ensure accurate predictions of component performance can be conducted digitally and specific to the manufacturing facility. This will then allow the incorporation of real time process data capture to refine process predictions in real time to assist in defect prediction and contribute to process control.

2 Integrated Design

The incorporation of design software with process simulation results will allow the improved prediction of performance allowing for the increased optimisation of component design with full material property utilisation.

3 M&P Boundary Conditions

Enhanced real-time data capture coupled with improved, connected simulation capability will enable the generation of ultra-high quality M&P boundary conditions which can feed back to generative design software and enable further optimisation of cast component design.

4 Fully Integrated DLMM

The combination of integrated design coupled with accurate simulation to provide a package that can fully exploit the DLMM capability.

Manufacturing & Processes

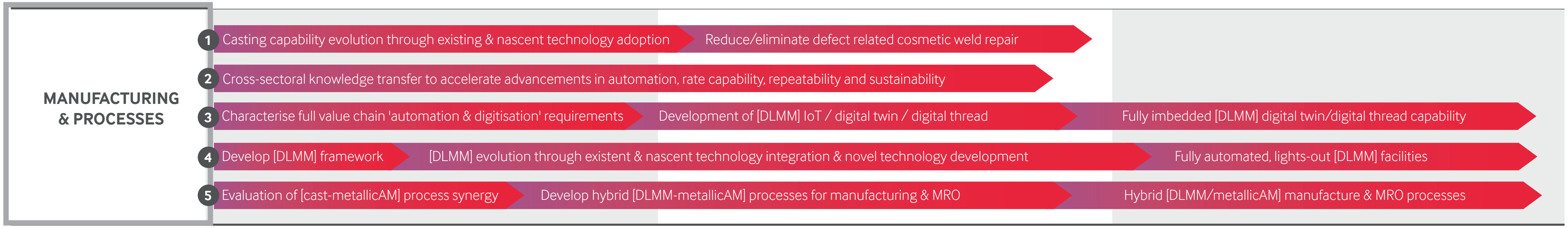
1 Process Improvement

Develop and evolve the current casting capabilities to improve repeatability and quality. Capture data throughout the process to drive improvement. Implement existing technologies into a new end-to-end process such as automated machining, inspection and repair. Improve metal cleanliness, utilising knowledge from academia and implement highly repeatable metal transfer processes such as counter gravity.

Moving forward, further improve the processes to significantly reduce or even eliminate defects and remove the necessity for cosmetic weld repairs.

2 Cross-Sector Knowledge

Take inspiration from other sectors, particularly automotive, where a casting revolution has occurred within recent years. For example, applying the automation and rate learning from automotive and developing this to meet the more stringent quality requirements of aerospace.



3 Digital Thread

Realise a fully digital thread through the entire casting process from design through until in-service and end-of-life, capturing all requirements for automation and digitisation, creating a feedback loop for continuous improvement. Link design, analysis, manufacturing simulation, process parameters, inspection results and operational history into a single 'Digital Twin' dataset.

4 Fully Integrated DLMM

This consultation has identified the requirement for a disruptive shift in shape casting technology and performance. Through a true holistic end-to-end philosophy spanning manufacture, assembly, operation and end-of-life, a Digital Liquid Metal Manufacturing (DLMM) process can enable the manufacture of high complexity, cost effective, sustainable, high performance aluminium components within a fully digital ecosystem.

5 Hybrid Casting, Additive Manufacturing

Casting and additive manufacturing should be seen as complementary processes. In the short term both processes face many of the same challenges around areas such as manufacturing repeatability and inspection, for example.

Moving forward there is the opportunity for hybrid cast and metallic AM parts, manufactured in a synergistic process to maximise the benefits of each technology into an optimal part.

Materials

APPROVALS, ALLOWABLES & SPECIFICATIONS
DESIGN & ANALYSIS
MANUFACTURING & PROCESSES

1 Optimise Existing Alloys

Using existing alloys (i.e. Al-Si-[X], Al-Cu-[X]), optimise performance and consistency through contemporary metallurgical understanding and improved liquid/solid metal processing.

Use these existing alloys to demonstrate the potential improvements through increased manufacturing process robustness.

2 Metal Circularity

Realise the sustainability opportunities presented by aluminium shape casting. Shorter term opportunities for reuse of manufacturing process scrap. Wider framework required to process end of life aerospace metals to avoid contamination and degradation. Develop greater understanding of the impact of impurities on material performance. Longer term objective of no primary aluminium use.

Finally, support full UK aluminium circularity, reducing CO_2 emissions by up to 95% vs. virgin material and reduce dependence on imported primary materials.

3 Alloy Evolution

Development of novel, fully circular, high-performance alloys, with high strength/high temperature alloys. Development with an ancillary focus to eliminate the need for heat-treatment, a increasing focus on recyclability, ability for integration with other Near Net Shape and Additive processes and a capability for in-service repair.

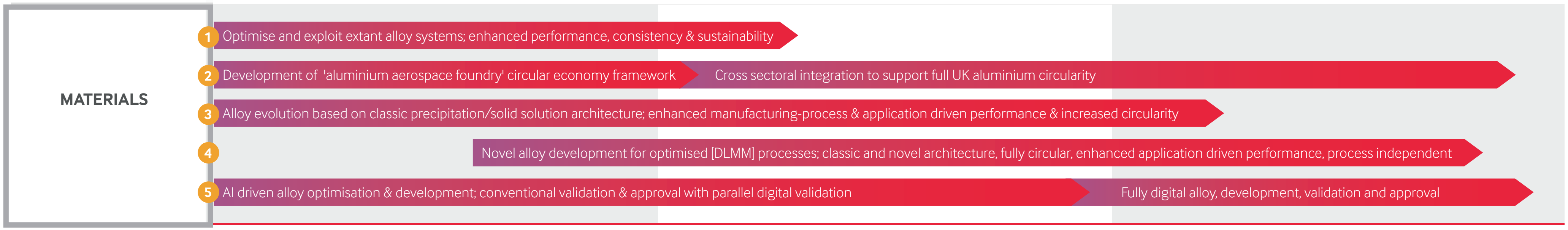
4 Novel Alloys

Further evolution of new alloys that are optimised for the DLMM processes. Full metal circularity, recycling end of life aerospace material without downcycling.

5 Digital Alloy Development

Develop and realise a digital platform for alloy development. Be able to predict the performance of alloys without the requirement to perform testing on a specific part-by-part basis.

High level of synergy in the next generation of alloys between casting and AM, through a digital alloy development platform.

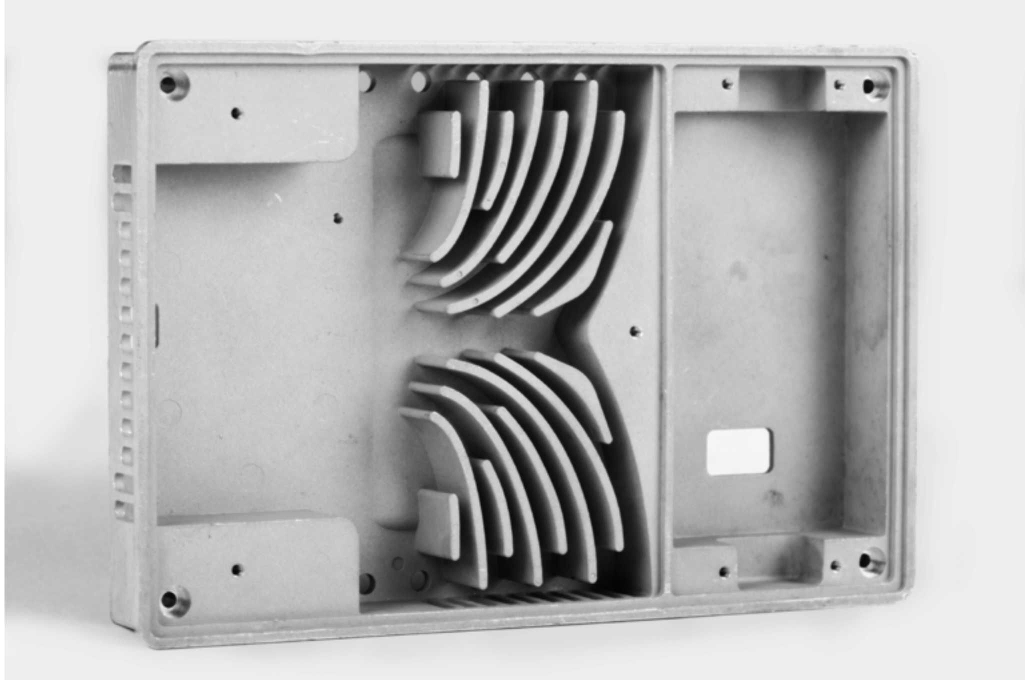


Glossary

AM	Additive Manufacturing
AMRC	Advanced Manufacturing Research Centre
ATI	Aerospace Technology Institute
BCAST	Brunel Centre for Advanced Solidification Technology
BEIS	Department for Business, Energy & Industrial Strategy
BtF	Buy-to-Fly Ratio
CT	Computerised Tomography
DC	Die Casting
DfM	Design for Manufacture
DLMM	Digital Liquid Metal Manufacturing
EoL	End of Life
EPSRC	Engineering and Physical Sciences Research Council
HPDC	High Pressure Die Casting
HVMC	High Value Manufacturing Catapult
IoT	Internet of Things
LiME	Liquid Metal Engineering Hub
MMC	Metal Matrix Composites
M&P	Materials & Processes
MRO	Maintenance, Repair & Overhaul
NDT	Non-Destructive Testing
NNS	Near Net Shape
OEM	Original Equipment Manufacturer
RTO	Research & Technology Organisation
TRL	Technology Readiness Level
UAM	Urban Air Mobility
UHBR	Ultra High Bypass Ratio
UTS	Ultimate Tensile Strength

More Info

Additive Casting®, 3D printed sand moulds with geometrically challenging undercuts and cavities. Image courtesy of Enable Manufacturing Ltd.



Small, thin walled, high complexity plaster mould investment castings for the aerospace industry, wall thickness 1-3mm. Image courtesy of Sylatech Ltd.

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