ATI AEROSPACE JOINING TECHNOLOGIES ROADMAP

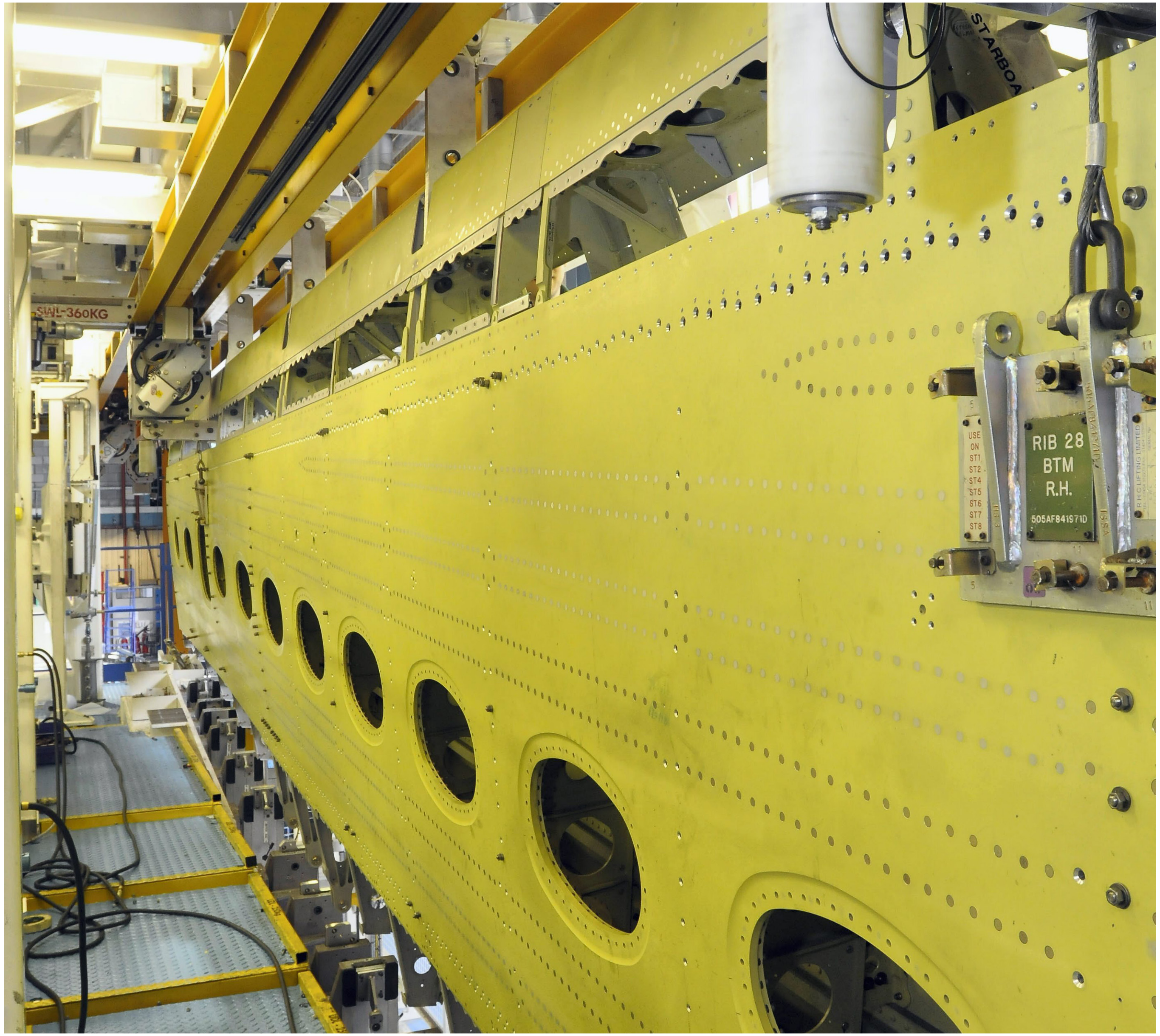
Foreword

Today, aircraft such as the Airbus A320 or Boeing 737, widely use mechanical fastening such as riveting for both component manufacture and large-scale assemblies. Mechanical fastening traditionally relies on manual installation. Although modern composite airframes employ much greater levels of automation in their production, they still rely on mechanical fastening, which prevents realisation of the full benefits of using integrated composite structures.

Advanced joining technologies, which include welding, bonding and the next generation of mechanical fastening processes can enable cost, weight and part count reduction, principally through reduced use of fasteners. There is a clear aspiration to eliminate fasteners by using direct joining processes including welding and adhesive bonding.

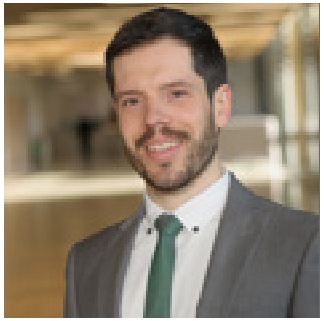
The development of future aircraft platforms fuelled by either SAF or hydrogen will present both challenges and opportunities for joining technologies. The prospective use of cryogenic liquid hydrogen fuel will demand high integrity joins, requiring extensive materials and manufacturing process characterisation.

This roadmap identifies the opportunities for advanced joining technologies in aerospace, spanning aerostructures, propulsion and systems. It is intended to be a guide to the UK aerospace sector from OEMs and their supply chains to academia and RTOs, to provide direction for future technology development and investment for joining technologies.



Use of mechanical fastening in assembly of A330 outer wingbox, image courtesy of Airbus.

Contributors



Joao Gandra

Joao Gandra is Principal Project Leader at TWI's Advanced Manufacturing Processes group. He specialises in welding and joining, acting as a consultant during product development, prototyping and technology transfer. He is also a technical lead for the friction welding and processing department at TWI, with responsibility for strategic roadmapping and innovation.

Most of his experience was gathered while working for the transport sector. He has led programmes delivering joining solutions for a variety of applications, including car body structures, commercial aircraft structures, thermal management systems for electric vehicles, high-speed rolling stock and satellite fuel tanks.

Before joining TWI, Joao completed a PhD in Manufacturing and Industrial Management at Instituto Superior Técnico in Lisbon, where he also worked as an assistant lecturer. In summary, Joao has consolidated 12 years of experience on joining and manufacturing, gathered in both academic and industrial environments.

Robert Scudamore

Robert Scudamore joined TWI in 2000 after a PhD in Materials Science and Engineering. TWI is a Research and Technology Organisation (RTO) that carries out development projects for industry in welding/joining, testing and inspection. He was initially involved with the joining of composites and plastics, but moved on to the processing of metallics. In 2004 he was promoted into management and is now Associate Director, Group Manager of the Advanced Manufacturing Technologies (AMT) Group. The Group covers metallic welding, additive, and other forms of materials processing.

Robert has been involved in various bodies to promote weld fabrication, joining and manufacturing. In 2013 he founded and Co-Chaired the European Welding/Joining Platform, an influencing body comprised of over six hundred entities across Europe that seeks to promote the funding of welding and joining projects by the European Commission. In 2015 he co-authored the Welding and Joining Strategic Research Agenda, a cross-sectorial view of the needs of European industry.

Matthew Bailey

Matthew is a Senior Technologist in the ATI's Structures, Manufacturing & Materials team, joining the organisation in May 2021. Matthew is responsible for metallic technologies including, but not limited to, joining, subtractive processes and near net shape technologies such as casting.

Before joining the ATI, Matthew worked for Airbus in a number of different roles. Having initially joined as a graduate in 2011, he subsequently spent nearly five years in research & technology, taking two composite technologies to TRL6 as Lead Engineer. Most recently, he was part of the Cost Engineering team, leading manufacturing costing support to numerous projects up to entire wing level responsibility, as well as actively contributing to the digital transformation of the costing team. Matthew has MEng in Aeronautical Engineering from Loughborough University and is a Chartered Engineer and member of the IMechE.

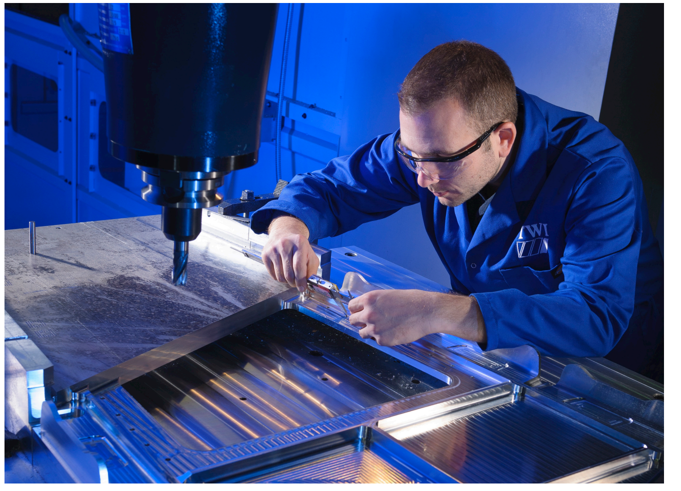
Introduction

Aligned with the latest ATI technology strategy, Destination Zero, advanced joining technologies including welding, bonding and the next generation of mechanical fastening technologies, are key to future component and assembly design, manufacture and through-life capabilities in aerospace. This encompasses all aerospace disciplines including aerostructures, propulsion and systems.

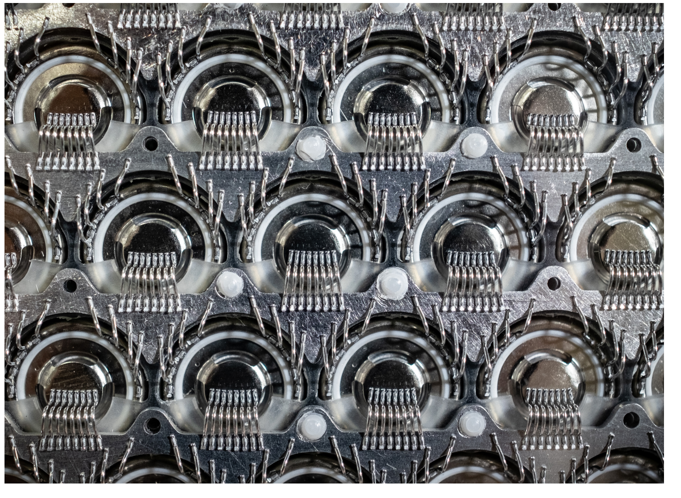
Joining technologies support the manufacturing targets of the ATI technology strategy for aerostructures through improving materials utilisation and reducing waste in manufacture by realising near net shape manufacturing. Production costs and in-service performance can be improved by enabling weight reductions through fastener elimination and more efficient structures.

Beyond aerostructures, advanced joining technologies will be an enabler for the next generation of propulsion and aircraft systems. Future electric powertrains, battery or fuel cell, will require high integrity, reliable and lightweight electrical connections.

To realise the benefits of advanced joining technologies, challenges such as inspection will need to be overcome. There is a need to be able to inspect interfaces with greater confidence, ideally in a fully automated process in-line with manufacturing operations. This is critical both to increasing confidence in these technologies, but also to achieve the future production rates.



Linear friction welded wing spar demonstrator – an example of joining technologies enabling tailored blanks, image courtesy of TWI.



Battery module for aerospace – joining technologies will enable future electric propulsion, image courtesy of Electroflight.

Roadmap Consultation

The ATI commissioned TWI to consult with key stakeholders in the UK to assess the present industrial landscape and survey the level of activity concerned with joining in the UK aerospace sector. The primary focus was to outline future R&D needs and understand their relationship with external market drivers and internal business needs. The data gathered during this consultation was analysed to inform the structured roadmapping process.

Close collaboration between TWI and the ATI enabled the population of the primary roadmap content over two workshops. Follow-up meetings with the original industrial stakeholders and other relevant organisations from academia and the Research and Technology Organisation network allowed gathering a consensus on the validity of the new roadmap, promoting initial awareness and instilling a sense of ownership at a national level.

The following organisations were consulted:

AIRBUS

VERTICAL Aerospace

BOEING

BAE SYSTEMS

Collins Aerospace

SAFRAN

GKN AEROSPACE

SPIRIT AEROSYSTEMS

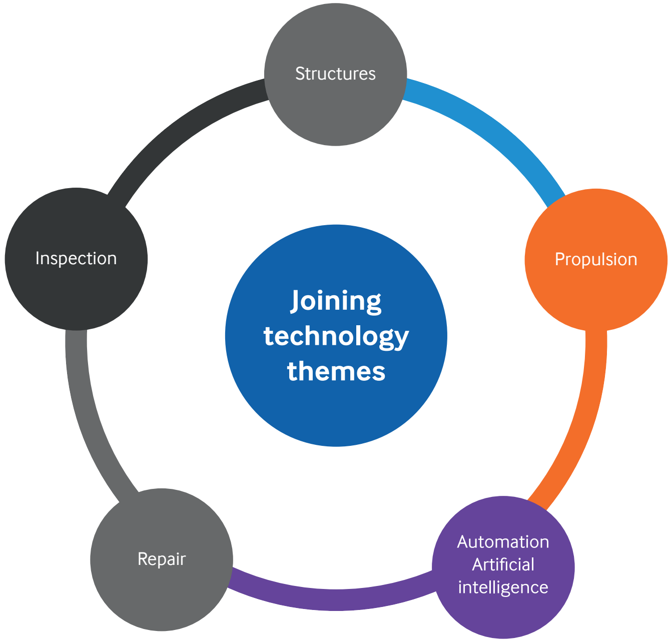
Rolls-Royce

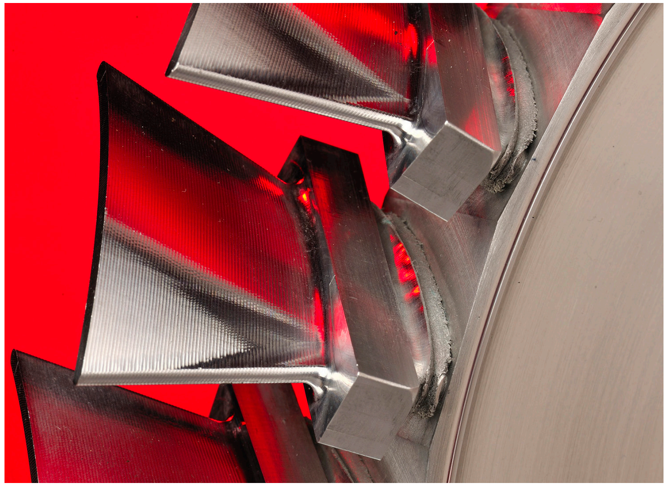
CATAPULT High Value Manufacturing

FUTURE Electrical Machines Manufacturing Hub

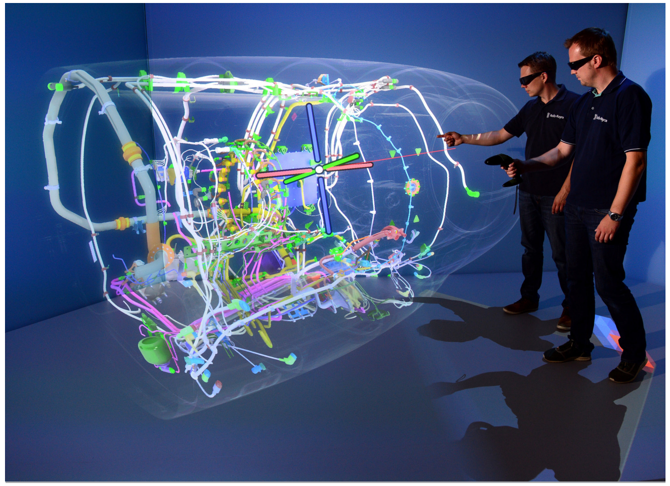
Consultation Conclusion & Roadmap

The consultation identified five key themes for joining technologies.





Linear friction welded compressor image courtesy of TWI.



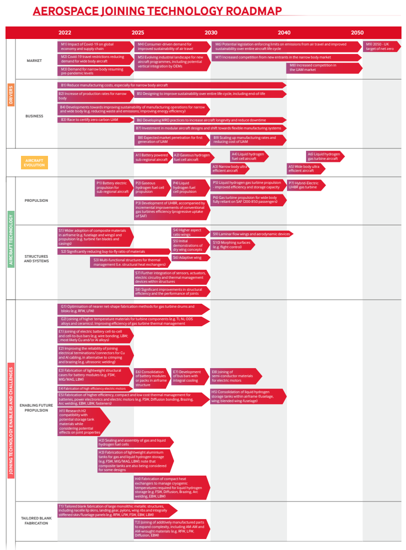
Future advanced systems will be enabled by joining technologies, image courtesy of Rolls-Royce

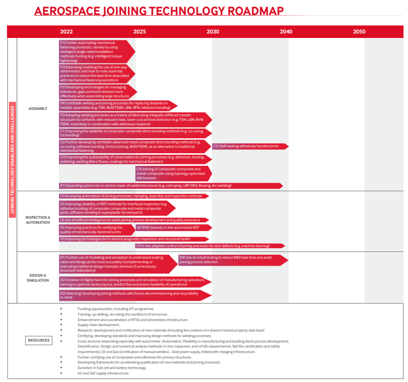
The two predominant themes were linked to Structures and Propulsion.

For Structures, topics were identified around replacement of fasteners, part segmentation and tailored blanks, challenges of higher aspect ratio wings and enabling a greater use of composite structures.

For Propulsion, topics identified spanned higher efficiency gas turbines, electric propulsion and hydrogen propulsion.

Finally Repair, Inspection and Automation identified themes around repair of more integrated structures and strategies for extending service, as well as in-line inspection, greater automation and in-situ process control.





View/download the joining roadmap -
www.ati.org.uk/publications/

Roadmap Context

The roadmap follows a Market Pull approach, where information is organised in multiple layers, aligned with a horizontal timeline of approximately 30 years to ensure the synchronisation of technology, product features and market trends. Five layers of information can be found:

1 **DRIVERS**

2 **AIRCRAFT EVOLUTION**

3 **AIRCRAFT TECHNOLOGY**

4 **JOINING TECHNOLOGY ENABLERS AND CHALLENGES**

5 **RESOURCES**

1 Drivers

Drivers expresses the most relevant market trends identified during the stakeholder consultation meetings. This layer was divided in two levels concerning the market and business drivers.

2 Aircraft Evolution

Aircraft evolution expresses ATI's prediction of how aircraft may evolve in the future. This timeline and aircraft nomenclature was set by the ATI's DestinATIon Zero strategy, which aims to achieve net-zero carbon emissions from commercial aviation by 2050.

3 Aircraft Technology

Aircraft technology identifies the generic aerospace technology building blocks required to enable the future aircraft concepts. The topics have been organised in the propulsion, structures and systems.

4 Joining Technology Enablers and Challenges

Joining technology enablers and challenges lists the key R&D topics that will enable the aircraft technologies identified. Some of the Joining technology topics also have a direct impact on the industry trends expressed in the top layer of the roadmap. When possible, examples of technologies/processes have been listed as potential solutions for each topic.

5 Resources

Resources is a supplementary section to identify resources enabling the industrial stakeholders in undertaking the R&D activities proposed. Some of these areas extend beyond the ATI's remit.

Joining Technology Enablers & Challenges – Enabling Future Propulsion

ENABLING FUTURE PROPULSION

- G1) Optimisation of nearer net-shape fabrication methods for gas turbine drums and blisks (e.g. RFW, LFW)
- G2) Joining of higher temperature materials for turbine components (e.g. Ti, Ni, ODS alloys and ceramics). Improving efficiency of gas turbine thermal management
- E1) Joining of electric battery cell-to-cell and cell-to-bus bars (e.g. wire bonding, LBW; ; most likely Cu and/or Al alloys)
- E2) Improving the reliability of joining electrical terminations/connectors for Cu and Al cabling, in alternative to crimping and brazing (e.g. ultrasonic welding)
- E3) Fabrication of lightweight structural cases for battery modules (e.g. FSW, MIG/MAG, LBW)
- E6) Consolidation of battery modules or packs in airframe structure
- E7) Development of bus bars with integral cooling
- E8) Joining of semi-conductor materials for electric motors
- E4) Fabrication of high efficiency electric motors
- E5) Fabrication of higher efficiency, compact and low cost thermal management for batteries, power electronics and electric motors (e.g. FSW, Diffusion bonding, Brazing, Arc welding, EBW, LBW, fasteners)
- H5) Consolidation of liquid hydrogen storage tanks within airframe (fuselage, wing; blended wing-fuselage)
- H1) Research H2 compatibility with potential storage tank materials while considering potential effects on joint properties
- H2) Sealing and assembly of gas and liquid hydrogen fuel cells
- H3) Fabrication of lightweight aluminium tanks for gas and liquid hydrogen storage (e.g. FSW, MIG/MAG, LBW); note that composite tanks are also being considered for some designs
- H4) Fabrication of compact heat exchangers to manage cryogenic temperatures required for liquid hydrogen storage (e.g. FSW, Diffusion, Brazing, Arc welding, EBW, LBW)

Joining Technology Enablers & Challenges – Enabling Future Propulsion

G1-G2 Higher Efficiency Gas Turbines

Continuing incremental improvements in gas turbine efficiency are required in the near-term. To improve fuel efficiency, engine compressor, combustor and turbine temperatures will increase, creating challenges for joining of higher temperature materials for compressor and turbine components (e.g. Ti alloys, Ni-based super-alloys, ODS alloys and ceramics), this may also include the joining of dissimilar materials. The use of high power / higher entropy brazing alloys were noted as a promising technology enabler for these high temperature materials.

Optimisation of manufacturing through near net-shape fabrication methods for compressor drums and blisks (e.g. RFW, LFW) is a key technology development.

There may also be developments to improve the efficiency of gas turbine thermal management through integral heat exchangers.

H1-H5 Hydrogen Propulsion

A future hydrogen propulsion system will create new challenges for joining technologies, with the manufacture of hydrogen storage tanks being the highest priority. The first generation tanks will probably be metallic, with composites coming later. Research will be required to understand the compatibility of potential tank materials with cryogenic hydrogen and the performance and integrity of joints. Lightweight aluminium tanks may be fabricated using techniques including FSW, MIG/MAG and LBW.

E1-E8 Electric Propulsion

Electric powertrain systems for battery powered sub-regional aircraft will require mature, certified joining methods to fabricate them. Some of these technologies are equally applicable to hydrogen fuel cell electric powertrains. These applications will demand high integrity, reliable and lightweight electrical connections.

Once these technologies are matured for aircraft, the next step would be to improving the gravimetric energy density by consolidating battery modules or packs within the airframe structure. Integrally cooled bus bars could dissipate excess heat from electrical machines, improving performance.

Higher efficiency electric motors may be enabled through better joining of stator lamination stacks and semi-conductor materials and reducing the weight of casings or shafts through lighter materials such as aluminium, magnesium or composites.

Performance gains are also possible by improving the conductivity and reliability of electrical terminations for copper and aluminium cabling which are traditionally joined by crimping or brazing.

Joining Technology Enablers & Challenges – Assembly

	2022	2025	2030	2040	2050

ASSEMBLY

- F1) Further automating mechanical fastening processes, namely by using intelligent single-sided installation methods/tooling (e.g. intelligent torque tightening)
- F2) Extending/enabling the use of one-way deterministic and hole-to-hole assembly practices to reduce the lead-time associated with mechanical fastening operations
- F3) Developing technologies for managing tolerances, gaps and build stresses more effectively when assembling large structures
- F4) Certifiable welding and joining processes for replacing fasteners in metallic assemblies (e.g. FSW, Refill FSSW, LBW, RFW, Adhesive bonding)
- F5) Adopting welding processes as a means of fabricating integrally stiffened metallic structures for airframe, with reduced mass, lower cost and low distortion (e.g. FSW, LBW, Refill FSSW, most likely in combination with adhesives/sealants)
- C1) Improving the reliability of composite-composite direct bonding methods (e.g. co-curing, co-bonding)
- C2) Further developing certifiable advanced metal-composite direct bonding methods (e.g. co-curing, adhesive bonding, friction joining, Refill FSSW), as an alternative to traditional mechanical fastening
- C5) Self-healing adhesively bonded joints
- C3) Improving the sustainability of consumables for joining processes (e.g. adhesives, brazing, soldering, welding fillers/fluxes, coatings for mechanical fasteners)
- C4) Joining of composite-composite and metal-composite using topology optimised AM brackets
- R1) Expanding options for in-service repair of welded structures (e.g. cold-spray, LBP-DED, Brazing, Arc-welding)

Joining Technology Enablers & Challenges – Assembly

F1-F3 Mechanical Fastening

One-way assembly would improve the productivity, reliability and lead time of fastener installation through more automation and deterministic assembly. Manufacturers also aspire to eliminate fasteners though adopting welding processes or adhesive bonding.

F4-F5 Welding for Metallic Aerostructures

The consultation identified an aspiration to replace mechanical fastening of metallics with welding or bonding. The primary challenges are characterisation and understanding performance of these joints to enable certification. The fabrication of integrally stiffened aerostructures is a route to weight reduction and lower production costs, providing distortion is minimised. Processes such as RFSSW were identified as promising, along with FSW and LBW.

C1-C5 Composites, Bonding & Sustainability

Joining solutions are key for extending the use of composite structures in aircraft. The reliability of direct bonding methods for composite-composite and composite-metal needs improvement. Processes identified for replacement of fasteners (currently the primary option for joining composite materials) include established methods of co curing, co-bonding and adhesive bonding along with joining of thermoplastic-based composites via induction heating and ultrasonic welding. Recent advances in friction riveting and RFSSW indicate potential for metal-composite joining and composite-composite for some material combinations. Longer-term, this technology area may benefit from advances in additive manufacturing from use of topology optimised brackets for fastening composite-composite and metal-composite assemblies.

R1 Joining for Repair

A recurring need captured during the consultations was more options for in-service repair of welded structures. As fasteners are currently the primary technique for airframe assembly, damaged components are replaced by drilling away the fastener elements. This is not possible for integrally joined structures and there is no consensus on what the repair solutions may be. Material deposition technologies are being considered for recovering surface damage or filling cracks . Some of the processes identified for metallic materials include cold spray, laser beam deposition and arc welding. A need to improve in-service prognostic inspection and structural health monitoring of joints was also expressed. One of the gaps in knowledge identified is the development of repair solutions for composites and adhesively bonded applications.

Joining Technology Enablers & Challenges – Tailored Blank Fabrication

	2022	2025	2030	2040	2050
TAILORED BLANK FABRICATION	T1) Tailored blank fabrication of large monolithic metallic structures, including nacelle lip skins, landing gear, pylons, wing ribs and integrally stiffened skin/fuselage panels (e.g. RFW, LFW, FSW, EBW, LBW)	T2) Joining of additively manufactured parts to expand complexity, including AM-AM and AM-wrought materials (e.g. RFW, LFW, Diffusion, EBW)			

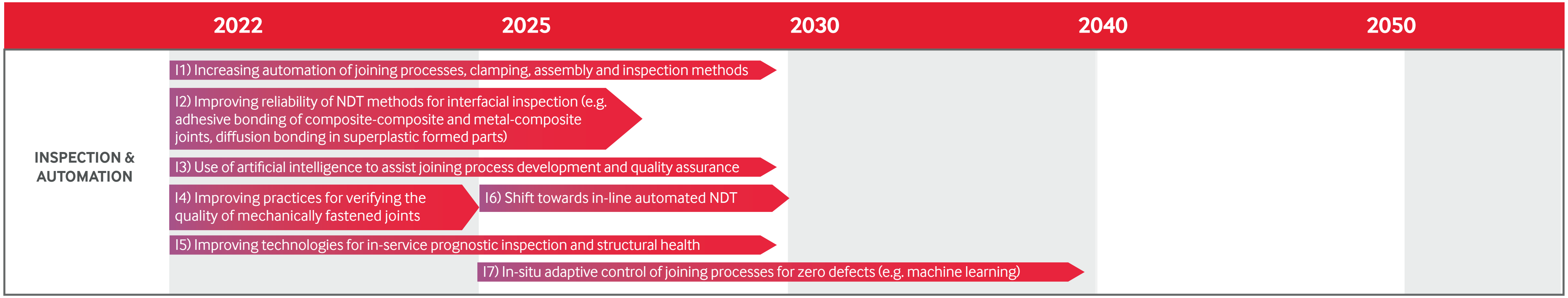
T1 Tailored Blank Fabrication

The use of welding for tailored blank fabrication of large monolithic metallic structures is economically promising for large components that are conventionally machined from solid. This includes nacelle lip skins, landing gear, pylons and wing ribs. In these examples, using smaller forgings or plates would enable savings in raw material costs and waste. The preferential processes selected for this approach are solid-state technologies based on friction and forge welding (e.g. RFW, LFW and FSW) as the joint microstructures can resemble the hot worked conditions of the original raw materials.

T2 Joining of Additive Parts

Longer term, an interest was expressed to work not only with wrought materials (e.g. plates, forgings) but also to join additively manufactured parts. This would allow higher design complexity and bypassing of machining access limitations. RFW, LFW, EBW and diffusion bonding would complement the capability of both powder bed and direct energy deposition processes.

Joining Technology Enablers & Challenges – Inspection & Automation



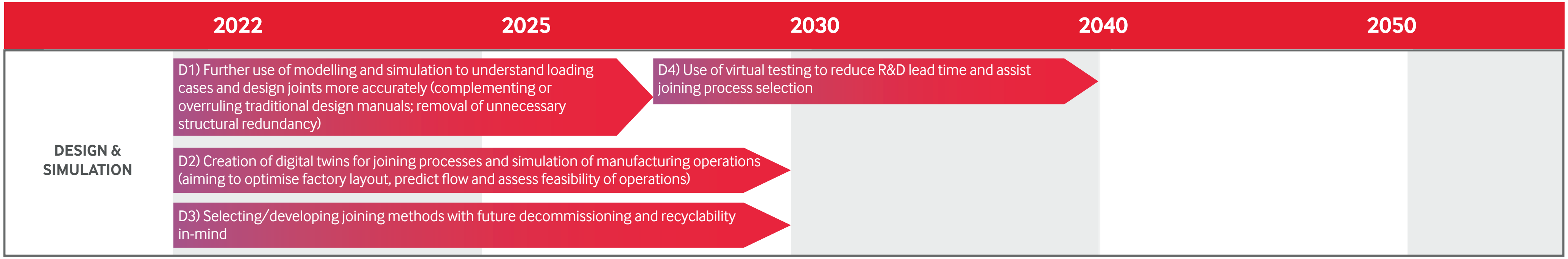
L1-L8 Automation

Several topics on inspection and automation were also identified. There was a general theme of increasing the level of automation of joining processes, clamping, assembly operations and inspection methods.

Greater use of joining techniques such as welding or bonding with be prerequisite on improving the reliability of NDT methods for interfacial inspection (e.g. adhesive bonding, metal-composite joints, diffusion bonding in SPF parts). This will subsequently grow confidence in the performance of these processes.

A shift towards in-process automated NDT, rather than off-line as today was identified. This would be combined with In-situ adaptive control of processes to support a 'zero defects' approach (e.g. using AI or machine learning), lessening the level of post-manufacture inspection required. The longer-term ambition is to solely rely on joining process control/monitoring for QA, reducing reliance on NDT and gathering data to eliminate 100% part inspection.

Joining Technology Enablers & Challenges – Design & Simulation



D1 Modelling & Simulation Tools

Today, design of aerospace assemblies, components and joints relies heavily on generic design manuals and standards. In future, extensive use of numerical modelling and optimisation tools would determine loading cases more accurately and tailor joint designs for each application. This is vital for removing unnecessary structural redundancy from systems and enabling further weight reductions.

D2 Digital Twins

The creation of digital twins for joining processes is also an area of critical development, aiming to optimise factory layout, predict flow and assess feasibility of operations. Longer-term, the use of virtual testing may help in reducing R&D lead-time and assisting joining process selection.

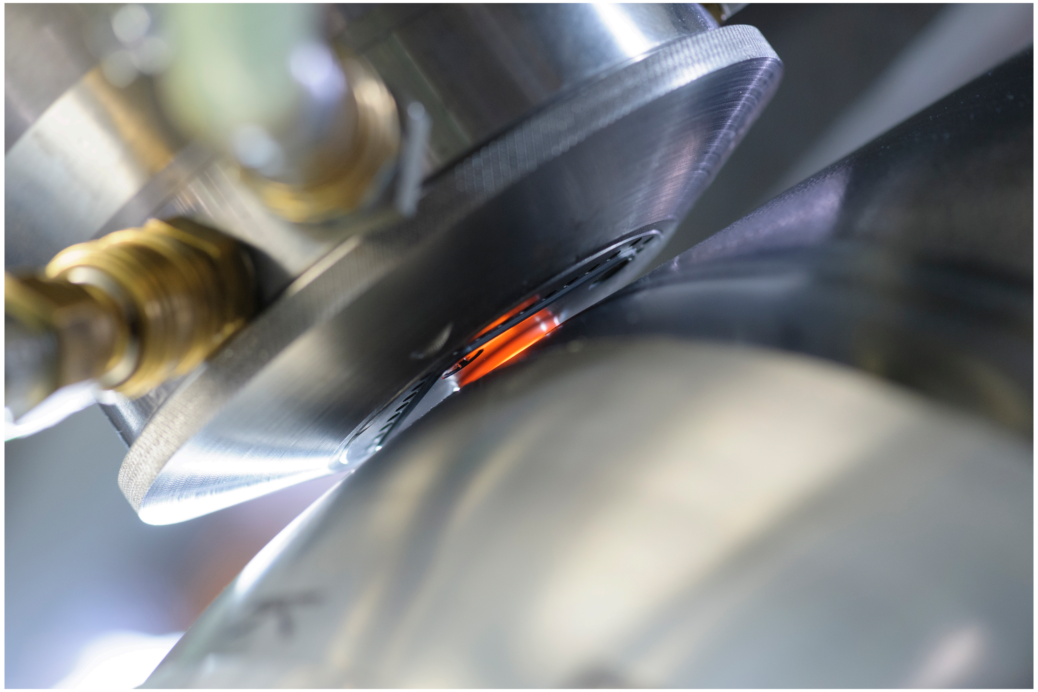
D3 Design for end of life

An important future design trend will be the selection/development of Joining methods with future decommissioning and recyclability in-mind. Although there are established methods for recycling metallic structures any dissimilar filler materials required for welding (e.g. required to prevent solidification cracking when fusion welding heat treatable aluminium alloys from the 2xxx, 7xxx and Al-Li series), adhesives/sealants or permanent fasteners will constitute a potential source of contamination when shredding and melting scraped metallic structures for recycling. There are some limitations in the amount of recycled material that can be used to manufacture original parts for aerospace to ensure low impurity content and structural integrity. In parallel, the value of any potential scrap metal at the end of the aircraft service will be closely dependant on the traceability of its chemical composition, which is hindered by the inclusion of impurities or contamination sources. Consequently, autogenous welding processes appear to be better for a sustainable design.

Glossary

AI	Artificial Intelligence
AM	Additive Manufacturing
ATI	Aerospace Technology Institute
EBM	Electron Beam Welding
FSW	Friction Stir Welding
FSSW	Friction Stir Spot Welding
LBP-DED	Direct Energy Deposition
LBW	Laser Beam Welding
LFW	Linear Friction Welding
MAG	Metal Active Gas
MIG	Metal Inert Gas
MRO	Maintenance Repair & Overhaul
NDT	Non Destructive Testing
OEM	Original Equipment Manufacturer
QA	Quality Assurance
R&D	Research & Development
RFW	Rotary Friction Welding
RTO	Research & Technology Organisations
SAF	Sustainable Aviation Fuel
TWI	The Welding Institute
UAM	Urban Air Mobility

More Info



Friction stir welding, image courtesy of TWI.

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