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ADDITIVE MANUFACTURE AND THE GAS TURBINE COMBUSTOR: CHALLENGES AND OPPORTUNITIES TO ENABLE LOW-CARBON FUEL FLEXIBILITY

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ABSTRACT

Advances in gas turbine (GT) combustion are enabled by metal additive manufacturing (AM) using selective laser melting (SLM) and other methods. In future low-carbon energy systems, AM will be critical for GTs operating on fuels such as hydrogen, ammonia, and biofuels. This paper evaluates the impact of AM on GT combustors, focusing on design freedom for novel geometries, reduced product development timelines, multiple component integration, and high-temperature materials suitable for harsh environments. Current AM challenges and research needs for GT combustors are discussed with industry input. These challenges are shown to be priority R&D areas across the GT value chain. Recent academic advances show the positive influence of widening access to SLM platforms and AM facilitates research using materials and geometries relevant to the GT community. Micro GTs are well-suited to SLM platforms, enabling novel geometries incorporating multiple functional parts including heat exchangers and porous media using advanced metal alloys. For industrial GTs, AM reduces new combustor product development time, as rapid prototyping and testing complements numerical methods. This review provides compelling evidence for continued AM R&D for GT combustion applications to meet future decarbonization goals.

NOMENCLATURE

AM	Additive Manufacturing
CFD	Computational Fluid Dynamics
CHP	Combined Heat and Power
DED	Direct Energy Deposition
DLN	Dry Low NO_x
ETN	European Turbine Network
GT	Gas Turbine
GTRC	Gas Turbine Research Centre
HTHX	High-Temperature Heat Exchanger
MGT	Micro Gas Turbine
OEM	Original Equipment Manufacturer
PBF	Powder Bed Fusion
PMB	Porous Media Burner
SLM	Selective Laser Melting
TAPS	Twin Annular Premixed Swirler
TRL	Technology Readiness Level

1. INTRODUCTION

The global market for additive manufacturing (AM), also known as 3D printing, was valued at >$10B in 2019 and is predicted to continue growing to over $30B by 2024 (McCue, 2019, SmarTech, 2020,). The number of EU AM projects subsequently increased from ~50 in FP7 to >400 in Horizon 2020 (European Commission, 2020a). This includes large investments such as the €18M AMAZE project (European Commission, 2017a) and the €15M MANUELA project (European Commission, 2020b). In the UK, AM projects totaling over £180M are currently active (UK Research and Innovation, 2020a), increasing by £165M from funding levels in 2012 (Hague et al., 2016). In the US, government investment in AM exceeds $400M (National Academies of Sciences, Engineering, and Medicine, 2020).

Gas turbine (GT) original equipment manufacturers (OEMs) have increasingly used AM for new product development, on-engine components, and repair of in-service equipment. This is evidenced by large investments from industrial GT OEMs, the establishment of industry groups such as the European Turbine Network (ETN) AM Working Group, and new events such as the Advanced Manufacturing and Repair for Gas Turbines Conference. EU research also supports AM for GTs and combustors, including the €5M OXIGEN project (European Commission, 2019a), which evaluated novel AM alloys for GTs, and the €1M ASLAM project (European Commission, 2017b), which investigated AM lean burn combustors.

Of the different AM technologies available to the GT industry, metallic powder bed fusion (PBF) by selective laser melting (SLM) represents ~80% of metal AM installations globally (SmarTech, 2019). Figure 1 shows a schematic of the PBF process, wherein sequential metal powder layers are wiped onto the component and melted via laser before repeating. PBF offers high component feature resolution, dimensional control, use of novel materials, and increased geometric freedom over subtractive machining (Frazier, 2014). However, controlling multiple build parameters, limited component size, and build time are challenges of PBF. Other AM technologies relevant to GT combustion currently under development include direct energy deposition (DED) (Mitsubishi Power, 2021), ceramics (Wang et al., 2019) and compositionally graded materials (Hofmann et al., 2014).

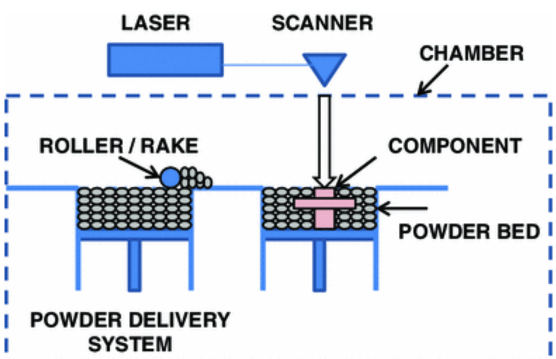

***Fig. 1** Schematic of PBF via SLM from Frazier (2014)*

The advantages of AM for GT developments are clear. For example, Siemens utilized metal AM for on-engine development of SGT-4000F turbine blades, validating multiple cooling concepts and reducing the blade development cycle by >75% (Fu et al., 2017). For combustion systems, GE/Baker Hughes note that the use of AM for NovaLT16 burner prototyping reduced development time and accelerated validation testing, achieving an overall savings of 50% (Sireesha et al., 2018). Similarly, Siemens claim that AM increased the speed of burner development for their SGT-600/700/800 GTs (Linstrand, 2019). To reduce GT component time-to-market, $1.3M was recently awarded to GE to reduce validation time of new AM parts by 50% using artificial intelligence to optimize multifunctional components. This data will be used for rapid prototyping and validation of optimized components (Gas to Power Journal, 2020b). Furthermore, the cost-competitiveness of AM is often considered in relation to traditional manufacturing. A significant body of research exists in this respect, which largely concludes that AM is cost-effective for small batch, prototype, and complex parts (Thomas, 2016).

In regard to the role of GTs in the low-carbon future, recent work by the National Academies of Science, Engineering, and Medicine (2020) specifies AM and combustion as high-priority research areas for GTs with specific goals including 100% H_2 operation and reducing CO_2 emissions while meeting NO_x emissions regulations. ETN (2020) recently highlighted the key combustion considerations that AM can help to address for fuel flexible H_2 GT combustors, including increased flashback risk in premixed systems, NO_x emissions, and metal temperatures.

This paper reviews the current state of the art in AM for GT combustion from three perspectives: academic research (Section 2), micro-GTs (MGTs) (Section 3), and industrial or heavy-duty GTs (Section 4). This analysis of challenges and opportunities intends to inform the future AM research direction and product developments required to enable low-carbon operation on fuels such as H_2, NH_3, and biofuels, allowing GTs to maintain their role in the energy transition and beyond.

2. AM IN ACADEMIC COMBUSTION RESEARCH

2.1 Overview of Academic AM Research

AM industry growth is accompanied by an increase in academic research output related to the AM process and its applications. Large investments have been made at universities to address the research challenges of AM. Key AM research centers include the Singapore Centre for 3D Printing at Nanyang Technological University (Khew, 2016), the Monash University Centre for Additive Manufacturing (Wood, 2017), the Center for Innovative Materials Processing through Direct Digital Deposition at Penn State University (2015), and the Direct Manufacturing Research Centre at University of Paderborn (2012). In the UK, universities in Nottingham, Sheffield, and Loughborough host leading AM research centers (Li et al., 2016). However, with increasing access to SLM machines, more universities are conducting research on low Technology Readiness Level (TRL) AM process optimization, monitoring, simulation, and materials (Schmidt et al., 2017). Universities also partner with industry on high TRL AM components and assemblies, such as the AM jet engine (Figure 2) developed by Monash University and SAFRAN (Wood, 2017).

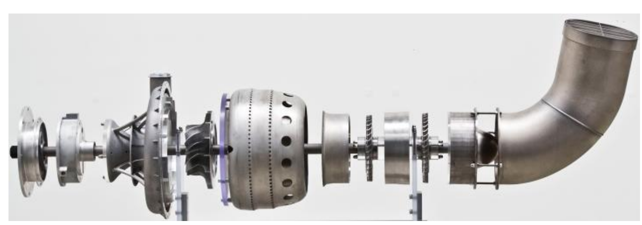

***Fig. 2** AM jet engine from Monash University and SAFRAN (Science in Public, 2015).*

2.2 Academic AM Combustion Research

While growth in the AM market has increased alongside academic AM research generally, specific research of AM for GTs has lagged in terms of time and number of publications, as shown in Figure 3. This was quantified by a structured literature search utilizing the SCOPUS database (Li et al., 2016). Nested wildcard keyword searches were performed with the following syntax:

ALL("Additive Manufactur*" OR "3D Print*") AND PUBYEAR = XXXX

This syntax returns all database publications containing any variant of "AM" or "3D Print" for a given publication year (2000-2020). Nested search terms were then added to the ALL operator to narrow the search results.

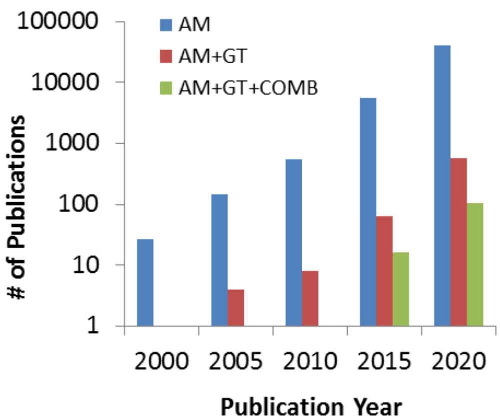

Fig. 3 *Publications related to AM, GTs, and combustion*

Exponential growth in AM research output is seen as publications increase by an order of magnitude every 5 years. AM research related to GTs and GT combustion lags the general trend by 5 and 15 years, respectively, which suggests significant room for research growth. This time lag may also be due to this search method only considering public research.

AM for academic combustion research falls broadly into three categories:

1. Components enabling fundamental combustion research
2. Low TRL novel combustion components
3. High TRL prototype combustion components

Examples of AM in fundamental combustion research focus on canonical flames to derive critical parameters such as flame speed or ignition delay. An AM window housing in a shock tube facility enabled ignition delay measurements of pressurized, preheated H_2/O_2 mixtures (Ninnemann et al., 2018). AM also produced cooling and air nozzles used in studies of laminar propane (Rivera et al., 2019, Figure 4.a) and turbulent syngas flames (Boyette et al., 2019, Figure 4.b), respectively. Cardiff University's Gas Turbine Research Centre (GTRC) incorporated an AM cooling nozzle for operation of a pressurized counterflow burner, also utilized for fundamental measures of flame speed and extinction behavior. The AM cooling nozzle (Figure 5.a) features an internal water channel surrounding each jet nozzle to regulate the gas temperature and jet velocity to enable flat flame stabilization. The design is a single stainless steel component fabricated using a Renishaw RenAM 250 PBF machine. To qualify the part and ensure build quality, the component was CT scanned (Metris X-TEK XTH450RT, Figure 5.b) by Warwick Manufacturing Group to identify any porosity or build defects before successful pressure testing.

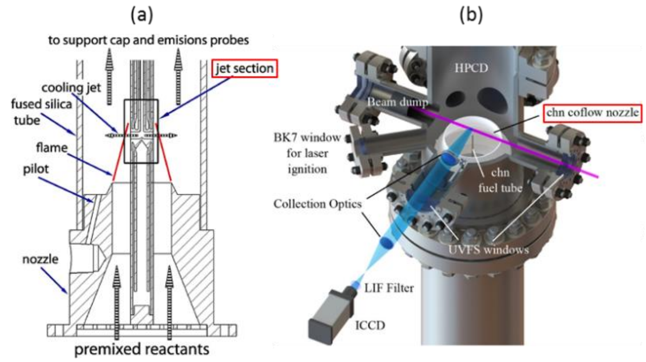

Fig. 4 *AM (a) cooling nozzle (Rivera et al., 2019) and (b) air nozzle (Boyette et al., 2019) used for fundamental flame studies, highlighted in red*

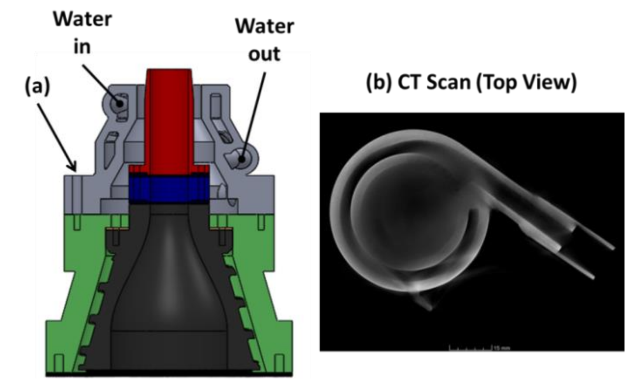

Fig. 5 *AM cooling nozzle (a) shown assembled with one-half of counterflow burner and (b) CT scan*

AM combustion components for use in low TRL research include swirlers, fuel injectors, and porous media burners (PMBs). With AM enhancing design freedom, unique geometries have been developed for combustion studies, with selected AM swirlers shown in Figure 6. The first swirler (Figure 6.a) was utilized for thermoacoustic instability studies with liquid fuels (Knadler et al., 2018). The triple swirler in Figure 6.b was based on the GE Twin Annular Premixed Swirl (TAPS) concept to evaluate unsteady interaction between swirling flows using high-speed diagnostics (Vashahi et al., 2018). The use of AM for this work enabled multiple TAPS injector designs to be evaluated with increasing swirl number in the outer radial swirler. The AM conical swirler (Figure 6.c) of the new Swedish National Centre for Combustion Technology burner was used for gaseous fuel studies in combination with 3D printed flow conditioners, mixing tube, and pilot flange (Hodzic et al., 2018). Finally, flame stability studies were conducted using novel Inco 718 AM helicoid swirlers (Giuliani et al., 2018, Figure 6.d), with the new

AM swirler designs shown to have better performance than the traditional design near the lean flame limit, however, surface roughness of the AM component was highlighted as a potential issue.

Further study of AM surface roughness effects on lean premixed flame stability and NO_x emissions was conducted using Inco 625 swirlers (Figure 7.a), manufactured by HiETA Technologies on a Renishaw RenAM 500Q machine (Runyon et al., 2020). Key findings include a NO_x reduction with increasing swirler surface roughness (Runyon et al., 2020). Surface roughness was also highlighted as a potential issue for AM liquid hydrocarbon fuel injectors, such as the AM air-blast atomizer used by Crayford et al. (2019) in a new rich-quench-lean burner (Figure 7.b).

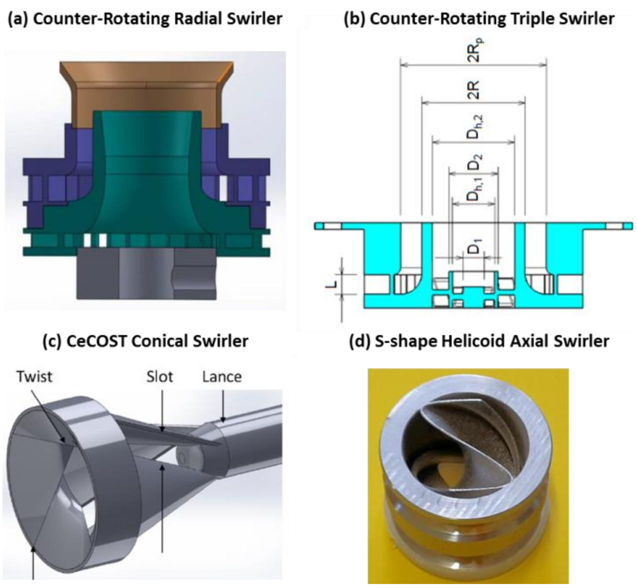

Fig. 6 *AM swirlers for combustion research, from (a) Knadler et al. (2018), (b) Vashahi et al. (2018), (c) Hodzic et al. (2018), and (d) Giuliani et al. (2018)*

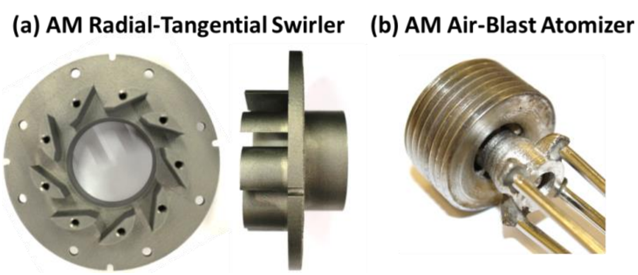

Fig. 7 *AM (a) swirler and (b) air-blast atomizer used in combustion research at the GTRC*

AM is also being used in academic combustion research on low-carbon fuels and cycles. For example, An et al. (2021) produced a new unconfined burner with a low-swirl injection nozzle and a flow-conditioning plenum manufactured by AM. This new burner was used to study flame/flow interactions for low-swirl burners using CH_4-H_2 blends, highlighting the importance of prototyping and testing for new AM designs using hydrogen. Fan et al. (2021) constructed a prototype multi-cluster Inconel burner using AM which features sub-millimeter (0.3 mm) diameter nozzles and complex manifold for combustion of H_2, O_2, and H_2O. Finally, the Southwest Research Institute have recently optimized a fuel injector design for AM to deliver complex swirling and mixing geometry in a 1 MW direct-fired combustor for a supercritical CO_2 power cycle (Delimont et al., 2021). Designing the fuel injector for AM will enable rapid changes to the design in upcoming test campaigns.

University-led combustion research also delivers AM components that are engine-ready items. In addition to the example from Monash University (Figure 2), Samara University fabricated a complete GT combustion can using NiCoCr powder in an SLM 280HL machine (Sotov et al., 2019, Figure 8.a). This combustion can was successfully tested on engine without operational penalty. An AM annular combustor (Figure 8.b) for a TA-8 GT will be used for biofuel GT development (Samara University, 2018). Additional ongoing projects aim to incorporate AM into existing GTs, such as a £1.4M UK Research and Innovation (2020b) project for demonstration of new AM combustion components in a zero-carbon H_2/NH_3 GT.

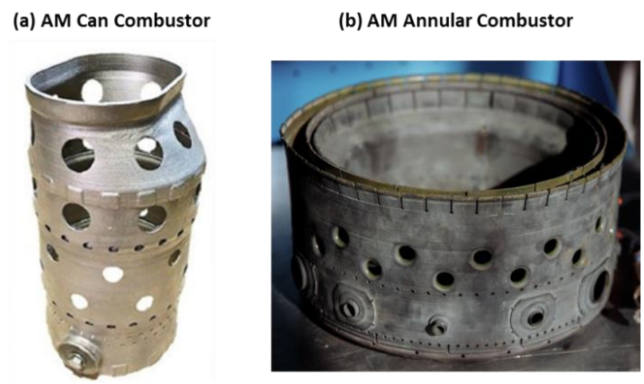

Fig. 8 *AM (a) can combustor (Sotov et al., 2019) and (b) annular combustor from Samara University (2018)*

For emissions reduction in low-carbon applications, AM PMBs are also under development at the university level, shown to suppress flame instabilities (Meadows and Agrawal, 2015) and reduce NO_x formation (Sobhani et al., 2019). AM PMBs with high spatial resolution and high-temperature materials can be built using topology optimization. The same concepts can also be applied to AM catalytic burners, which have been shown to enable low-temperature H_2 combustion (Dubbe et al., 2019).

3. AM FOR LOW-CARBON MICRO GTs

3.1 Overview of MGT Combustion Applications

According to the ETN MGT Technology Summary (2018), fuel flexibility, emissions reduction, and AM of high-temperature materials are key future research activities for MGTs, generally defined as GTs with power outputs below 1 MW. Current EU projects support this research need, including the €3M FUTURBINE project developing a 400 kWe combined heat and power (CHP) MGT (European Commission, 2020c) and the €4M NextMGT project to create decentralized hybrid grids between renewable energy generation and industry (European Commission, 2020d).

To increase cycle efficiency and reduce fuel consumption, MGTs often employ a recuperated combustion system whereby the combustor inlet air is preheated by the turbine exhaust using a high-temperature heat exchanger (HTHX). MGTs typically produce < 500 kWe and heat in CHP applications, improving cycle efficiency from ~30% to ~80% (Boukhanouf, 2011, Bhatia, 2014). Further benefits such as low maintenance cost, compact size, noise reduction, fuel flexibility, and low emissions make MGTs ideal for remote, portable or distributed cogeneration applications (Enagi et al., 2017).

MGTs are also used in low-carbon applications. Sung et al. (2017) showed that an MGT running on biogas increased its economic feasibility with a bottoming organic Rankine cycle. Kurata et al. (2017) utilized gaseous NH_3-air in a 50 kWe MGT, achieving 96% combustion efficiency and recently improved performance achieved reductions in NO_x and NH_3 emissions (Kurata et al., 2019). Additionally, Aurelia Turbines, DLR, and REWAG have partnered to design a new combustor for the Aurelia A400 MGT to operate on a blend of H_2 and natural gas up to 100% H_2 operation (Fuel Cell Works, 2019).

3.2 AM for MGT Combustion

Taking into consideration the compact size of MGTs, their increased design complexity, and the range of materials required, PBF AM is suitable for fabrication of MGT components including new combustors, topology-optimized HTHXs, and porous media (Frazier, 2014). For small components, AM offers the benefit of multifunctional structures, reduced production tooling cost, and increased design freedom (Delgado et al., 2018). These advantages translate into improvements in MGT size, weight, lead time, assembly cost, fuel flexibility, and efficiency (Ngo et al., 2018).

One key component for MGT efficiency and combustor design is the recuperator, which accounts for 25% of the MGT cost (ETN, 2018). For MGTs, plate-and-frame and plate-fin exchangers offer improvements in heat transfer density (800-1500 m^2/m^3) over shell-and-tube exchangers (50-100 m^2/m^3) and are therefore the focus for MGT applications (Zhang et al., 2018a). For HTHX manufacture, AM has gained attention due to its ability to fabricate complex geometries with high-temperature metals while incorporating optimized topology for heat transfer surfaces. The available range of metal alloys for SLM HTHXs includes Aluminum 6061, stainless steel 304/316, Al-Si-10Mg, and Inco 718 and 625. Ongoing AM material developments include CM247LC and Haynes 282 for high-temperature applications (ETN, 2018). Current developments for ceramic (e.g., SiC) AM are slower, due to challenges in component density and joining layers effectively. Further research would benefit ceramic AM due to its potential in high-temperature MGT applications (Klein et al., 2018).

HTHXs have been built using AM for applications including exhaust waste heat recovery (Kennedy et al., 2019a, Figure 9.a), and a novel inverted Brayton-Rankine cycle (Kennedy et al., 2019b). For MGT applications, a novel recuperator (Figure 9.b) has been built with optimized heat transfer surfaces to reduce size and cost.

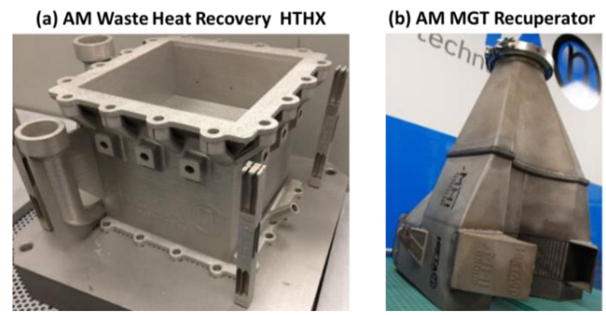

Fig. 9 *AM HTHXs including (a) waste heat recovery (Kennedy et al., 2019), and (b) MGT recuperator (ETN, 2018)*

Gerstler and Erno (2017) fabricated four AM oil coolers from Aluminum, Ti-6Al-4V, Co-Cr, and Inco 718. When compared to a conventionally manufactured HTHX, the AM HTHX resulted in 66% weight reduction, 50% volume reduction, and removal of all brazed joints. A sectioned view of this AM HTHX (Figure 10.a) highlights its complex manifold and internal structure.

OEMs also incorporate AM directly into MGT combustion systems. For example, Euro-K developed and tested a new Inco 718 dual-fuel combustion can (Figure 10.b) for a Bilfinger MGT (EOS, 2018). Printed on an EOS M290 machine, the can size was reduced by 20%.

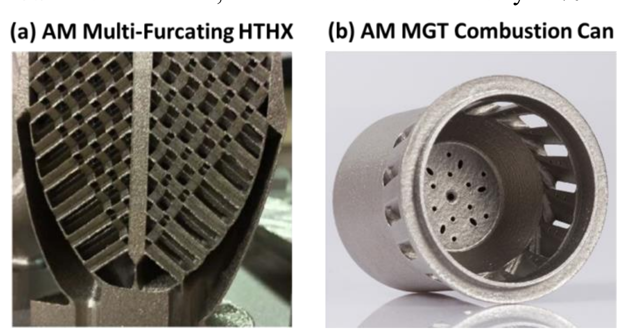

Fig. 10 *AM (a) HTHX (Gerstler and Erno, 2017) and (b) MGT combustion can (EOS, 2018)*

Research has also been conducted in development of MGT combustion systems using AM liquid fuel injection with complex internal passages and heat transfer surfaces to improve vaporization and reduce NO_x emissions (Adamou et al., 2019). This injector was integrated in a swirl-stabilized MGT combustor, and favorable flame stability and emissions were observed. Proprietary MGT combustor designs are also under development taking full advantage of AM's design freedom to incorporate a can combustor with an annular radial flow recuperator (Figure 11). Utilizing high-temperature materials, this design aims to increase MGT efficiency due to increased fuel preheating and waste heat recovery (Jones and Smith, 2020). The design also incorporates porous channels to enable air flow to cool the combustor walls.

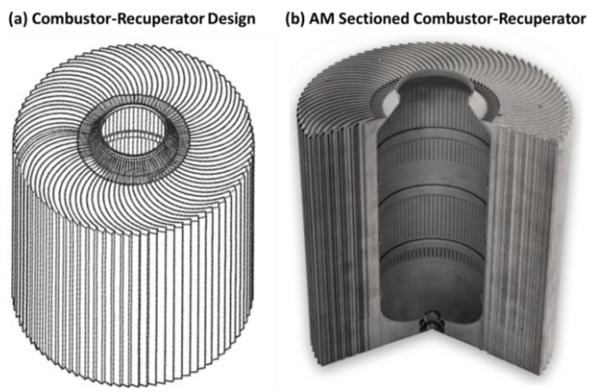

Fig. 11 *Combustor-recuperator (a) design (Jones and Smith, 2020) and (b) sectioned AM build (HiETA Technologies, 2020)*

AM technology also facilitates novel metal porous media structures with varying unit cell geometries to improve MGT performance. While porous media are used to enhance convective heat transfer, they also offer advantages for evaporation, boiling, catalytic reaction, and combustion applications. However, implementation in HTHXs and MGTs is currently limited by difficulties printing complicated geometries, powder removal, and control of build parameters (Jafari and Wits, 2018).

3.4 AM Challenges for MGT Combustors

There are several challenges to be addressed to allow further utilization of AM for MGTs. Regarding the fabrication stage, high initial AM machine costs are compounded by expensive powder materials, and as such an effective business case must be made. In addition, inadequate AM process repeatability may lead to inferior mechanical properties and decrease in combustion performance. This is particularly true for fuel/air mixing geometries (e.g., injectors) where build inconsistency and poor surface finish can result in clogging, increased pressure drop, and knock-on effects such as hot spots, excess emissions and flame instabilities (Klein et al., 2018, Ngo et al., 2018). Combustion uniformity can also be influenced by the size consistency of AM holes in these geometries. If liquid biofuels are to be used, challenges arise regarding the use of AM channels within injectors to provide heat transfer to maintain component temperature and control of vaporization rates to avoid pre-combustion. Developing small-scale flame stabilization methods also remains a challenge. The effectiveness of the chosen stabilization mechanism (e.g., swirl-stabilized, bluff bodies, or porous media) depends on designs which reduce combustor pressure drop and noise, improve mixing, and enable cooling of the combustor liner and flame stabilizer.

Additionally, there are challenges associated with integration and sizing of the MGT HTHX and efficient distribution of HTHX outlet air in the combustion chamber. Heat transfer affects combustion efficiency by controlling the physical state of reactants and products. However, modelling heat transfer to increase efficiency while ensuring reliable operation is challenging (Jafari and Wits, 2018). Also, as AM enables multiple component integration between the HTHX and MGT combustor, differential expansion within monolithic designs must be accounted for during design to avoid operational failure.

3.5 AM Research Needs for MGT Combustors

Based on literature review and industry input, research needs are identified to address the challenges of AM in MGT combustors. In terms of the AM process, research is needed to enhance data acquisition and control of the build process, with a view to characterizing build consistency in-situ and providing process feedback (Zhang et al., 2018a). Increasing the geometrical accuracy and improving the surface finish of components by optimizing printing parameters will increase process efficiency while reducing combustor component lead time and cost. In terms of process modelling, advanced tools predicting the thermo-mechanical properties and surface finish of combustor components should also receive scientific attention. A proper understanding of the roughness and emissivity of the parts is necessary as they affect pressure loss, mixing, and metal temperatures which influence the combustion system. Therefore, AM of complex structures, such as channels for air and fuel distribution or internally-cooled micro-structures for porous and catalytic combustion surfaces, would be less challenging and better component life prediction could be obtained. Additionally, in-depth understanding of AM surface roughness and its interaction with heat transfer microstructures requires development of advanced combustion CFD capabilities with conjugate heat transfer (Jafari and Wits, 2018).

Further research is needed into the development of new metallic and ceramic alloys with optimized topology, aiming to deliver advanced thermomechanical properties to extend the MGT combustor operating limits. Material interactions under varying operating conditions should also be examined to improve multifunctional designs (Huang et al., 2015, Ngo et al., 2018). Finally, a simple MGT research platform for qualification of new combustion components and configurations should be developed, with a focus on improving system modularity, reducing development time, and improving MGT performance, particularly with fuels such as H_2 and NH_3.

4. AM FOR FUEL-FLEXIBLE INDUSTRIAL GTs

4.1 Overview of Low-Carbon Industrial GTs

Industrial GT OEMs committed to develop GTs capable of 100% H_2 operation by 2030 (ETN, 2020). While achievable in GTs operating steam-diluted diffusion flames, further work is needed to develop fuel-flexible, lean premixed combustors capable of operating from 100% natural gas to 100% H_2 within emissions regulations. GT combustors capable of operating with other low-carbon fuels such as NH_3, biomethane, and liquid biofuels will also be required while supporting the existing GT fleet through repair and retrofit. AM has a role in bringing these new designs and strategies to market.

Given the difficulties associated with burning H_2, namely increased flame temperatures (increasing turbine inlet temperatures and NO_x emissions) and higher flame speeds (flashback potential and increased pressure drop), OEMs have developed unique strategies for its use. In 2015, GE completed a US Department of Energy project to develop advanced high-H_2/syngas combustion systems, and AM was utilized throughout the project (York et al., 2015). Over 30 fuel-air premixer concepts were developed, printed, and tested, including new swirl premixer and micromix concepts (Figure 12). This micromixer concept is now utilized in GE's dry low NO_x (DLN) combustor (DLN 2.6e) with testing indicating 50% H_2 operation may be possible (Goldmeer, 2019).

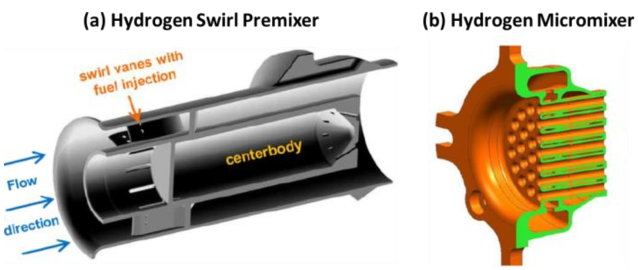

Fig. 12 *GE (a) swirl premixer and (b) micromixer for high-H_2 combustors (York et al., 2015)*

Siemens have a range of H_2 capability in their fleet, from 50% H_2 for the largest GT, SGT5-9000HL, up to 100% H_2 in wet diffusion mode in their aeroderivative SGT-A35 (Linstrand, 2019). Ansaldo Energia demonstrated in preliminary testing that the GT-36 sequential combustor can operate up to 70% H_2 without any derating, and up to 100% H_2 with reduction in firing temperature (Bothien et al., 2019). In Japan, significant investment has been made to develop H_2 and NH_3 GTs with the aim to commercialize by 2030 (Mitsubishi Heavy Industries, 2020). Mitsubishi demonstrated operating capability up to 30% H_2 and is developing a DLN multi-cluster combustor for 100% H_2 operation (Dodo et al., 2015, Figure 13.a). Kawasaki also developed a H_2 micromix combustor in partnership with RWTH Aachen University (Tekin et al., 2018, Figure 13.b).

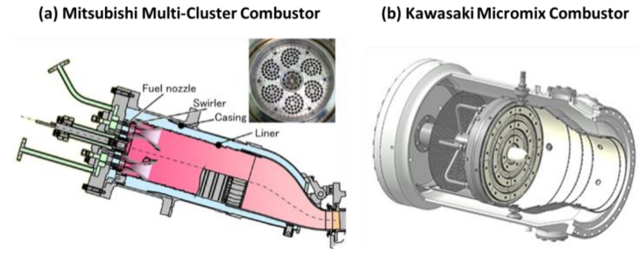

Fig. 13 *H_2 combustor concepts from (a) Mitsubishi (Dodo et al., 2015) and (b) Kawasaki (Tekin et al., 2018)*

4.2 AM in Industrial GT Combustors

AM has a role to play in the development of low-carbon, fuel flexible GT combustion systems. This will enable GTs to secure their role in the energy transition and provide dispatchable demand response to support renewable energy installations. This is evident as the OEMs have made large investments in AM technology. GE invested \$1.4B to purchase AM equipment suppliers Arcam AB and SLM Solutions Group AG (Brooks, 2016). Siemens made recent large investments (>€30M) in AM technology for a variety of GT applications (Gas to Power Journal, 2020a), including combustor design, retrofit, and repair in part by acquiring an 85% stake in Materials Solutions Ltd, an AM company specializing in GT components (Brooks, 2016). MAN Diesel and Turbo invested €2.6M in the MAN Centre for Additive Manufacturing (Flin, 2017). In September 2020, Mitsubishi Power opened AM-Zone in Japan to promote metal AM methods and technologies (Roan, 2020). There is evidence of nearly all GT manufacturers including GE (Sieger, 2017), Siemens (Larfeldt et al., 2017, Navrotsky et al., 2015), MAN Diesel and Turbo (Flin, 2017), Mitsubishi (Kitamura et al., 2019), Ansaldo Energia (Maurer et al., 2016), Solar Turbines (Dryepondt et al., 2019), and Baker Hughes (Sireesha et al., 2018) researching and utilizing AM to produce new components and repair of in-service equipment to extend product life (Andersson et al., 2017). This also includes low-TRL fundamental studies on the impact of AM build parameters (e.g., laser power, laser speed, hatch distance) on the structure of porous media (Fantozzi et al., 2019) and the ability to capture AM component surface roughness in CFD (Kapsis et al., 2020).

Examples of AM for industrial GT combustion include a new fuel/air mixing nozzle (Figure 14.a) for GE's HA-class GT, which eliminated the need for thousands of brazed joints, increasing reliability and combustor efficiency (Sieger, 2017). Amongst over 450 AM production parts, GE/Baker Hughes developed an AM combustion swirler (Figure 14.b) for oil and gas applications (Kellner, 2016) along with an AM fuel burner (Figure 14.c) for use in their NovaLT16 GT (Sher, 2020). Solar Turbines has produced AM parts such as an Alloy X fuel nozzle (Jamshidinia et al., 2017, Figure 14.d). MAN Diesel and Turbo intend to extend AM production to combustion chambers, burners, and nozzles (Flin, 2017).

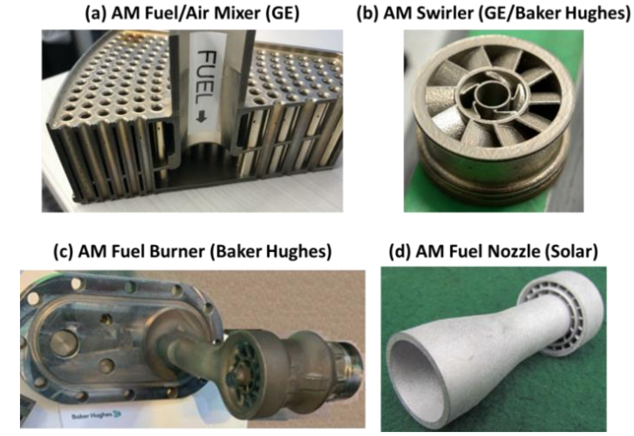

Fig. 14 *AM combustion components from GT OEMs including (a) GE (Sieger, 2017), (b) GE/Baker Hughes (Kellner, 2016), (c) Baker Hughes (Sher, 2020), and (d) Solar Turbines (Jamshidinia et al., 2017)*

Siemens produced full AM burners for SGT-600/700/800 GTs. The original third-generation burner design (Figure 15.a) included 13 machined parts with 18 welds and an external pilot gas feed line. The AM burner is a single part resulting in a 75% reduction in lead time and 20% reduction in weight (Larfeldt et al., 2017, Figure 15.b).

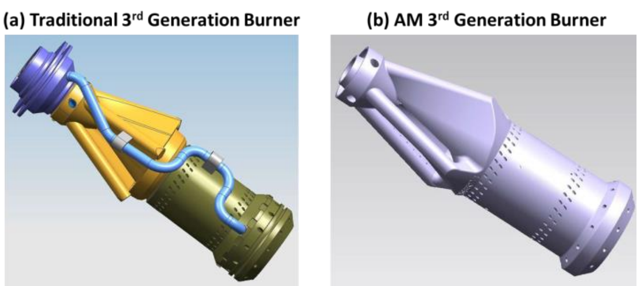

Fig. 15 *3rd generation Siemens SGT-600/700/800 (a) traditional and (b) AM burner (Larfeldt et al., 2017)*

Other Siemens industrial GTs benefit from AM combustion components, including the SGT5-9000HL (Burke, 2018), the aeroderivative SGT-A05 premixer (Siemens AG, 2018, Figure 16.a), and the SGT-A35 (Panfili et al., 2019). Additional burner components include an SGT-1000F swirler (Figure 16.b) and burner nozzle pilot cone (Fu et al., 2017, Figure 16.c). Siemens also patented a novel AM dual fuel helicoid mixer shown as "21,22" in Figure 16.d (Bonaldo, 2017).

Recent work by both Ansaldo Energia and Mitsubishi Power confirms that combustion applications are a high priority for the use of AM in GTs, even if the manufacturing method employed differs. Ciani et al. (2021) detailed Ansaldo's new Center Body Burner (Figure 17.a) for its sequential combustion system. This burner concept was fabricated using SLM to deliver both liquid and gaseous fuel in a single component whereas the traditionally manufactured design required more than 100 parts and 50 welds. Mitsubishi Power (2021) have also utilized AM for combustion components, such as that shown in Figure 17.b, which was fabricated using DED rather than SLM to produce a geometry weighing 13 kg and printed in 3 hours.

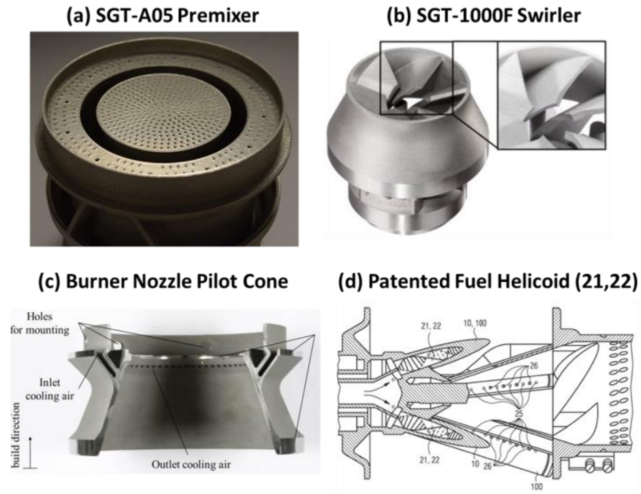

Fig. 16 *Siemens AM combustion components including (a) SGT-A05 premixer (Panfili et al., 2019), (b) SGT-1000F swirler and (c) burner nozzle pilot cone (Fu et al., 2017), and (d) patented dual fuel injector (Bonaldo, 2017)*

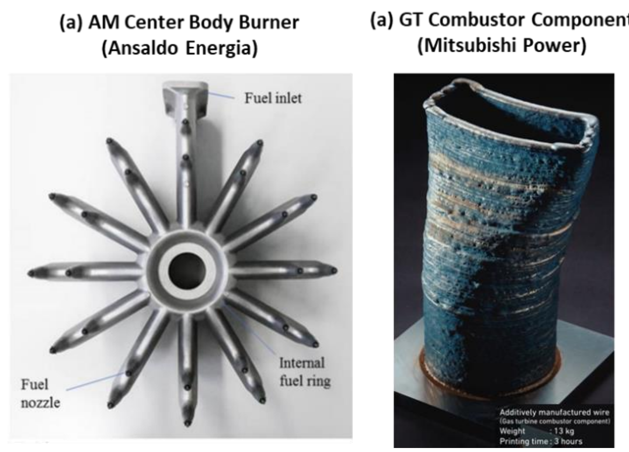

Fig. 17 *AM combustion components from (a) Ansaldo Energia (Ciani et al., 2021) and (b) Mitsubishi Power (2021)*

New GT combustion components will be required in the future for low-carbon applications, and patents often show these developments as AM enables unique, patentable designs. For example, GE patented an AM combustor head with integrated cooling to protect fuel injectors from high temperatures during H_2 combustion (DiCinio and Melton, 2017). Furthermore, novel AM fuel injector designs have been patented, such as the GE trapped vortex injector (Melton, 2016, Figure 18.a) and an Ansaldo Energia swept fuel injector (Loeffel et al., 2020 Figure 18.b).

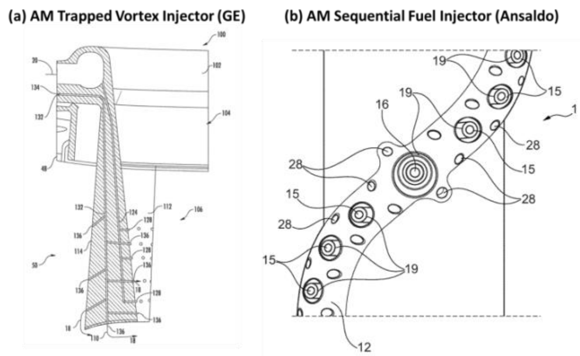

Fig. 18 *Patented AM fuel injectors from (a) GE (Melton, 2016) and (b) Ansaldo Energia (Loeffel et al., 2020)*

These new AM combustion systems often need to be proven in single can tests and on-engine applications, including tests with high H_2 volumes (Larfeldt et al., 2017). In 2017, Siemens installed an AM SGT-700 burner which successfully operated for >8000 hours at E.ON's Philippsthal CCGT plant (Patel, 2018, Gas to Power Journal, 2020a). In December 2019, Siemens partnered with Göteborg Energi to install an SGT-800 at the Rya CHP plant in Sweden to use for testing fuels such as H_2 (Siemens AG, 2019). AM burners are a key part of the project for operational validation and accelerating R&D. A project was also announced in partnership with Braskem Petrochemical Complex in Brazil, during which two SGT-600s will operate on process gas up to 60% H_2 by 2021 (Gas Turbine World, 2020). AM is also used in these burners to improve burner tip cooling for high-H_2 operation. Finally, GE has successfully retrofitted AM combustion components including fuel injection lances and thermal dampers to control low-frequency combustion oscillations as part of the GT26 High Efficiency upgrade at Uniper's Enfield Power Station, which will increase power output, efficiency, and maintenance intervals (Prandi, 2019, Walton, 2021).

4.4 AM Challenges for Industrial GT Combustion

In addition to the AM challenges for MGT combustors (Section 3.4), there are specific challenges in incorporating AM into industrial GT combustion system design, production, and use in the field. Fu et al. (2017) highlight that AM is often not well perceived by designers, leading to ineffective use of AM during GT component design. Furthermore, GT components have rigorous design requirements, which require an understanding of the AM process and material properties alongside new AM design workflows (Fu et al., 2017). AM GT combustor designs also require unconstrained thinking that integrates multiple disciplines (e.g., heat transfer, aerodynamics, and mechanical integrity).

Moving from validated design into serial AM production has also proved challenging for industrial GTs, including machine setup, repeatability, and always-on manufacturing (Fu et al., 2017). Other AM production challenges for industrial GT combustion systems include powder availability within the supply chain, health and safety considerations particularly around powder handling and machine cleaning in production environments, and geometric scale limitations of current AM platforms unable to produce large components. In terms of implementation in the field, AM has shown promise to produce spare parts for oil and gas applications (Sireesha et al., 2018), however challenges arise in terms of GT operator uptake of AM products due in part to concerns about long term product risk management, AM design longevity, and reliability compared to traditional parts.

Zero-carbon fuels such as H_2 and NH_3 provide unique challenges for AM utilization in industrial GT combustion systems. Existing experience with high-H_2 diffusion flames and lean premixed process gas flames needs to be extended with AM to incorporate combustor cooling designs for injectors, liners, and guide vanes to protect against higher temperatures while reducing air use. In addition, GT combustors will be challenged by high NO_x emissions with H_2 flames, requiring development of fuel/air mixing strategies incorporating AM. Experience with NH_3 in industrial GTs is limited; however, due to its low reactivity and fuel-bound nitrogen, its use will be challenged by high NO_x emissions requiring a shift away from lean premixed concepts towards rich-quench-lean combustor designs with unique fuel and air injection strategies. In addition, NH_3 pre-vaporization and cracking into H_2 and NH_3 to catalyze the combustion reactivity may be required to avoid excessive NH_3 emissions.

4.5 AM Research Needs for Industrial GT Combustion

In addition to AM research needs identified for MGT combustors (Section 3.5), unique research needs were developed with industry input for industrial GT combustion systems. Research needs are identified for each AM step of design, production, and implementation. In terms of design, upskilling of GT designers and university training is needed with a focus on AM design methodologies, AM processes, and AM material characteristics. Research is also required into the development and application of topology optimization and machine learning tools that can incorporate the wide design parameter space for optimizing AM combustors, considering material properties, heat transfer, aerodynamics, acoustics, fuel properties, and chemical reactivity. In terms of production, further research is required into AM costs in comparison to conventional manufacturing, with a specific need to include AM build and powder cost optimization during the design process. Further research is also needed into powder materials for specific combustion applications to enhance material utilization, including ceramic AM development to improve combustor efficiency. Production research also needs to consider new AM repair schemes for existing components.

Specific research needs are also identified for implementation of new AM combustor designs in the field. New designs, repair strategies, or retrofits must be proven throughout the development cycle, including bench testing up to full engine demonstration to build confidence. An integrated engineering approach must be developed to identify where AM can be used for subsystems and across multiple GTs. Third, longitudinal AM combustion product and material reliability studies and information sharing across the GT value chain are needed to improve GT user support for uptake of new AM products.

Digital data capture and utilization is a constant thread of research need throughout the AM steps discussed, including data generated during the design process that can be directly input into the AM production process, monitoring of AM build parameter data and build quality data, test and qualification data generated for new AM combustor designs, and long-term reliability data to improve user confidence in AM adoption. Data feedback loops are required at each stage to identify failure mechanisms, synergies, and optimization opportunities.

6. SUMMARY AND CONCLUSIONS

As the global AM market grows, opportunities abound for GT OEMs and research organizations to partner in the development, fabrication, testing, and implementation of novel low-carbon combustion systems. The transition to low-carbon fuels will build on existing experience and require rapid development of new high efficiency, low emissions systems. By reviewing the current state of the art for AM in combustion systems across three specific sectors, academia, MGTs, and industrial GTs, the following conclusions can be drawn:

AM for Academic Combustion Research:

- Academic research into AM has increased exponentially from 2000-2020, however research into AM for GT combustion specifically lags by ~15 years, showing significant room for growth in this area.
- Metal AM is being widely utilized in academia as access to SLM machines increases.
- AM is mainly used to make components (e.g., nozzles, swirlers, injectors) which enable fundamental and low TRL combustion studies.
- High TRL component manufacture is limited, but large-scale investments encourage this activity.
- Low-carbon AM burner designs are being investigated, supported by research funding and industry partnerships.

AM for MGT Combustion:

- The geometric scale of MGTs is well-suited to current AM platforms enabling multiple component integration and multifunctional components.
- AM offers opportunity for the optimization of MGT recuperators to improve efficiency through topology optimization of heat transfer surfaces and new high-temperature metallic and ceramic materials.
- AM should be used to enable H_2 and NH_3 use and extend fuel flexibility through porous media and catalytic combustion.
- AM cost, consistency, powder removal, and surface finish are key challenges for small-scale fuel injection, heat transfer, and flow distribution components.
- Key research needs include improved AM process modelling, CFD tools with conjugate heat transfer, and a MGT platform for new component qualification.

AM for Industrial/Heavy-Duty GT Combustion:

- Nearly all OEMs are researching, incorporating, and patenting AM in combustion systems, with a focus on fuel injection, fuel/air mixing, and component cooling.
- OEMs are active in fundamental and applied low-carbon combustion studies and are using AM in on-engine combustion systems to increase operability with H_2.
- AM is identified as a key technology for reducing development time and cost of industrial GT combustion components.
- Key AM challenges include AM design knowledge, moving into serial production, and novel cooling and mixing designs for low-NO_x H_2 and NH_3 utilization.
- Key AM research needs include training in AM design, digital design tools to optimize the wide combustor parameter space, new materials, and long-term component reliability studies to build GT user trust.

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