ROADMAP FOR THE INDUSTRIALIZATION OF ROBOTIC CONTINUOUS ULTRASONIC WELDING OF FIBER REINFORCED HIGH-PERFORMANCE POLYMERS IN THE AEROSPACE INDUSTRY

M. Janek*, L. Larsen*, S. Jarka*, D. Görick*

* Deutsches Zentrum für Luft- und Raumfahrt e.V., Zentrum für Leichtbauproduktionstechnolgien, Am Technologiezentrum 4, 86159 Augsburg, Deutschland

Abstract

The aerospace sector is progressively integrating fiber-reinforced high-performance polymers, due to their superior strength-to-weight ratio, corrosion resistance, and design flexibility. Conventional joining methods, such as mechanical fastening or adhesive bonding are labor-intensive, defect-prone, and costly, therefore limiting manufacturing efficiency. Ultrasonic Welding (UW) of thermoplastic composites has emerged as a rapid, adhesive-free joining technique that employs high-frequency vibrations to produce robust and high strength bonds. UW enables the assembly of complex geometries while minimizing weight, material waste, and processing time, thereby enhancing design freedom and structural integrity. In aerospace, UW facilitates the fabrication of lightweight, high-performance structures that comply with stringent safety and regulatory standards, eliminates drilling and riveting-induced damage, and supports innovative architectures previously unfeasible. This review summarizes the principles of static and continuous UW, highlights its advantages, and surveys current aerospace applications, with emphasis on the different development milestones. A roadmap towards industrial maturity is outlined, calling for coordinated efforts among industry, academia, and regulatory bodies to standardize processes, certification, and qualification of UW joints. Advancing UW to full commercial readiness promises to transform airframe manufacturing, unlocking the widespread adoption of this technology for next-generation aircraft.

Keywords

CFRP; Joining Technologies; Ultrasonic Welding; Thermoplastics; Thermosets, Robotics

NOMENCLATURE

Symbols

ϵ_0	strain amplitude	[-]
E''	loss modulus	Pa
ω	angular frequency	rad/s
$\dot{Q}_{avg}$	average heat dissipated	W

Abbreviations

AFP	Automated Fiber Placement
AMC	Acceptable Means of Compliance
ANAC	Agência Nacional de Aviação
CFRP	Carbon Fiber Reinforced Polymers
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CS	Certification Specifications
EASA	European Union Aviation Safety Agency
ED	Energy Director
FAA	Federal Aviation Administration
ICAO	International Civil Aviation Organization
LMPAEK	Low Melt Polyaryletherketone
LSS	Lap Shear Strength
MFFD	Multi Functional Fuselage Demonstrator
NDT	Non-Destructive Testing
NRC	National Research Council of Canada
PA	Polyamides
PC	Polycarbonates
PEEK	Polyetheretherketone
PEI	Polyetherimide
PEKK	Polyetherketoneketone
PPS	Polyphenylenesulfide
TCCA	Transport Canada Civil Aviation
TRL	Technology Readiness Level

doi: 10.25967/650147

1. INTRODUCTION

Civil aviation currently constitutes the predominant modality for long-haul intercontinental passenger transport and is undergoing a period of accelerated expansion. Forecasts produced before the onset of the COVID-19 pandemic projected that global air traffic would increase approximately three-fold over the 2020-2050 horizon. Although the pandemic had a significant impact on air traffic, similar to other events such as the global financial crisis in 2008, it can be assumed that the growth trajectory will resume with a similar gradient. [1]

According to the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) administered by the International Civil Aviation Organization (ICAO), total carbon-dioxide emissions from global civil aviation have been estimated at 608 million metric tonnes for the year 2019. [2, 3]

The growing reliance on air transport, coupled with the imperative to continually lower emissions due to the climate-forcing characteristics of this greenhouse gas, creates a direct conflict between operational demand and environmental objectives. The commercial aviation accounts for more than 70% of annual fuel consumption of aerospace applications, thereby representing a major source of emissions of climate-forcing gases. Furthermore, air freight transportation and General Aviation also contribute proportionately to the civil share of emissions. Consequently, mitigating total emissions can be achieved by employing efficient, innovative lightweight aircraft designs, followed by an overall reduced fuel consumption respectively. [1]

The joints between components in modern aircraft are typically comprised of standard fasteners such as screws, bolts, and rivets. In a commercial aircraft, the number of rivet connections can vary based on its size, with larger metallic aircraft containing approximately 100000 titanium rivet joints, which are particularly prevalent in specialized assemblies like the vertical tail plane. The economic potential of reduced fastener usage extends beyond production costs, as it can also reduce operating costs of the aircraft. For example, up to a 5% reduction in the overall weight of specific aircraft structures can be achieved through the elimination of fasteners and an optimized design that eliminates additional weight associated with effects such as bearing stress and other boundary conditions. These cost savings can be significant and contribute to the overall efficiency and profitability of aircraft operations. [4]

Therefore, new joining technologies such as the welding of thermoplastic and thermoset composites can significantly improve the economic and ecological balance in the application of Carbon Fiber Reinforced Polymers (CFRP). In conjunction with various alternative joining technologies such as resistance welding, induction welding, or laser welding, ultrasonic welding provides a means of joining thermoplastic or functionalised thermoset composite materials by melting the composite material locally and cooling it again under consolidation pressure in a defined time and controlled manner. [5]

The following sections will describe the mechanism of ultrasonic welding, detail its various application procedures, and present the current state of the art. Additionally, a strategic plan will be developed outlining the necessary steps for the process to reach the level of technological maturity required for serial and industrial application in the aerospace industry.

2. PROCESS PRINCIPLE

Ultrasonic welding is classified as a frictional welding method that involves exposing the adherends to be joined to high-frequency and low amplitude ($\approx 100\mu m$) mechanical vibrations, in addition to a static welding force. [6] The ultrasonic welding assembly illustrated in Fig. 1 is composed of four principal elements: a power source, a piezoelectric converter, a vibration-amplifying (or attenuating) booster, and a sonotrode (also referred to as a horn). [7]

The power source receives the low-frequency mains voltage (either 50Hz or 60Hz) and, through a frequency-conversion stage, generates an alternating electrical signal in the ultrasonic range, most commonly around 20kHz. This high-frequency signal drives the converter, where a stack of piezoelectric disks undergoes rapid expansion and contraction in direct proportion to the applied voltage, thereby converting electrical energy into a precisely controlled mechanical oscillation. [8, 9]

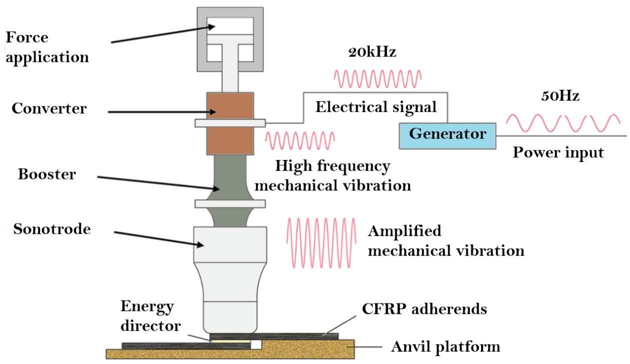

FIG 1. Ultrasonic welding - process principle. Image modified from [7].

The booster, whose geometry can be tailored to either increase or decrease the displacement amplitude, acts as a mechanical transformer that matches the output of the converter to the requirements of the downstream sonotrode. The sonotrode fabricated from high-strength, low-density alloys such as titanium or aluminium alloys is the interface that delivers the ultrasonic vibration to the workpiece. Its external contour and the size of the contact area are selected according to the specific joint geometry and the material being welded, ensuring optimal energy transfer and uniform pressure distribution. [9]

All components of the equipment are dimensioned and tuned so that their natural resonances coincide with the operating frequency supplied by the ultrasonic generator, which maximizes the efficiency of the energy conversion chain. Beneath the sonotrode, an anvil provides a rigid backing for the CFRP laminates. The laminates are held in the desired orientation by a dedicated fixturing system that secures them throughout the welding cycle. The complete stack is forced against the anvil by a static load generated by either a mechanical or pneumatic actuator; this load establishes the necessary clamping pressure that, together with the ultrasonic vibration, produces the weld. [8]

In many thermoplastic CFRP joints, a thin layer of thermoplastic material, known as an Energy Director (ED) is introduced at the interface. Through maximum dissipation effects, the ED acts as a localized heat-generation zone: the ultrasonic energy is concentrated within its geometry, causing rapid softening of the thermoplastic and facilitating material flow that bonds the adjoining laminates. The shape of the energy director (triangular, semi-circular, rectangular, or thin-film configurations are typical) has a pronounced effect on the heat concentration, melt pool development, and ultimately on the mechanical integrity of the resulting weld. [8, 10, 11]

Benatar and Gutowksi introduced a multiphase model for ultrasonic welding, consisting of five stages: mechanical and vibrational dynamics, viscoelastic heating, heat conduction, flow dynamics, and intermolecular diffusion. Furthermore, Benatar and Gutsowksi have proposed a method for calculating the viscoelastic heating rate during ultrasonic welding, which involves the angular frequency (ω) of the welding apparatus, the loss modulus (E'') and the strain amplitude (ϵ_0) of the material [10]:

$$\dot{Q}_{avg} = \frac{\omega \cdot E'' \cdot \epsilon_0^2}{2} \qquad [W] \tag{1}$$

Equation (1) provides a more accurate understanding of the heating process during ultrasonic welding and is an important consideration for optimizing the welding process. [10]

3. OPERATIONAL MODE

Ultrasonic welding can be categorized into two distinct operational modalities. The first modality involves a static and localized application, whereas the second modality employs a continuous and dynamic approach to generate weld seams in an uninterrupted manner.

3.1. Static Ultrasonic Welding

The principle of ultrasonic welding, first introduced in the context of a static process for bonding pure polymer joints, has been in existence for many decades. This technique, characterized by its swift execution, economic efficiency, and high degree of automation, has found extensive application in mass production. Researchers, such as Benatar and Gutowski, recognized the significant potential of this joining technology for the application on high-performance thermoplastic composites. They augmented the understanding of the process by developing a simulation model grounded in its fundamental principles, mechanics and vibrations, the viscoelastic heating and heat transfer mechanisms, the flow and wetting process and the intermolecular diffusion during the solidification phase. [10]

Benatar and his co-researchers sought to enhance the comprehension of the process through an investigation of the adherends thickness. By defining a thickness limitation of 6mm for the sonotrode and the welding interface, they successfully established the difference between far-field and near-field ultrasonic welding. [12, 13]

In 1994, Kempe and Korger-Roth of the Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR) identified the considerable potential of the ultrasonic welding process. Initial spot welding activities were conducted to explore the applicability of this process to carbon fiber-reinforced Polyetheretherketone (PEEK). The weld trials included the analysis of spot welds on similar and dissimilar part thicknesses as well as the investigation of the overall weld strength dependent on the distance between multiple spot welds. [14] An investigation into multispot ultrasonic welding was performed, which discovered the potential of this method in multispot applications. The research revealed that the first weld spot influences the necessary energy of subsequent spots. Equal weld energy for the first and second spot, led to a reduced strength and overall area of bond. On the other hand, the displacement required for an optimal weld result (strength and quality) remains unchanged outlining the potential of displacement controlled ultrasonic welding. [15, 16]

Nowadays, the ultrasonic welding process has experienced a resurgence of interest in the past 15 years, with both academia and industry investigating various aspects and effects related to energy directors and interface surfaces. The research conducted by Villegas and fellow researchers has focused on optimizing weld quality through the use of different energy directors. The results have shown that statically welded specimens can achieve a Lap Shear Strength (LSS) of up to 35-40 MPa through the use of appropriate appliance of the energy director. [17, 18]

Further investigations were conducted to determine the potential of a resin-poor and energy-director-less welding procedure, that concluded that a resin-rich interface between the adherends leads to improved overall weld quality. One of the most common validation values, the LSS, decreased by approximately 50% in the most unfavorable case when the pure resin ED was significantly reduced. [19, 20]

Further studies were undertaken to examine the effects of various process parameters, including travel speed, vibration amplitude, power consumption, displacement, processing forces, and resultant

pressures, in order to gain a more comprehensive understanding of the process dynamics. [18, 21–23]
In conclusion, a foundational understanding of static ultrasonic welding has been established, enabling the consistent production of high-quality welds with predictable strength and reliability.

3.2. Continuous Ultrasonic Welding

Another operational mode of ultrasonic welding, characterized by increased dynamism is Continuous Ultrasonic Welding (CUW). This process involves the generation of a continuous weld seam through the sustained application of ultrasonic vibrations to the semi-finished parts, concurrent with the continuous motion of the welding end-effector along the predetermined weld seam geometry. In contrast to traditional static ultrasonic welding, where all tasks such as pre-clamping, active vibration, and consolidation pressure during solidification are performed by the sonotrode, continuous ultrasonic welding employs a segmented approach, wherein these tasks are decoupled and executed in a sequential manner. The aforementioned tasks are discretized and executed by distinct components, specifically: (1) the pre-clamping roller, which applies the initial pressure; (2) the conventional sonotrode, which generates the ultrasonic vibrations; and (3) the consolidation unit, which provides the necessary pressure during solidification, as illustrated in Fig. 2. Furthermore, an anvil with clamping mechanisms (4) & (5) is employed, as shown in the figure, to secure the semi-finished parts or the top and bottom adherend plates, as illustrated in the laboratory example of producing single lap shear specimens.

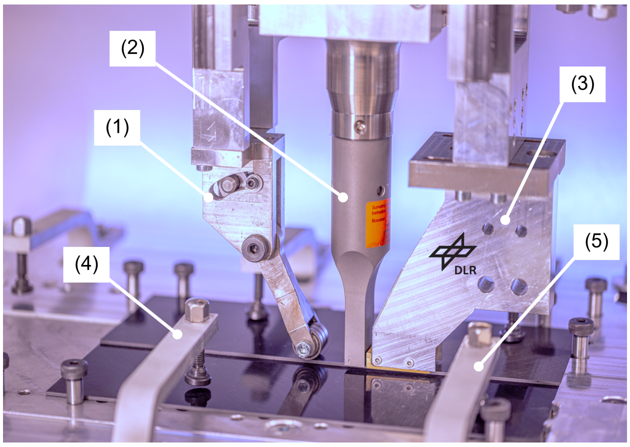

FIG 2. Continuous ultrasonic welding - functional elements and weld setup. Image modified from [24].

This apparatus can be integrated with either a single-axis linear test bench, as depicted in Fig. 3, or a multi-axis robotic system, as illustrated in Fig. 4, thereby enhancing trajectory flexibility and enabling the creation of complex three-dimensional paths.
A linear axis test bench is utilized for the development of the welding process and the fundamental

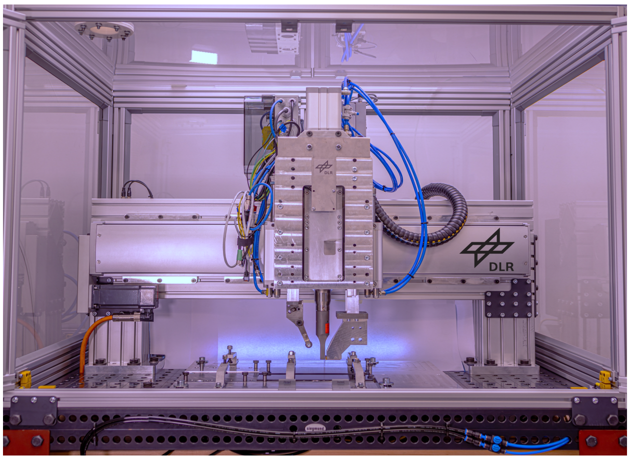

FIG 3. Continuous ultrasonic welding end-effector mounted to a linear axis test bench. Image modified from [24].

analysis of innovations within the setup, whereas the robotic application serves to demonstrate the ultimate objective of industrializing the process and establishing its presence in the industry. Engelschall et al. introduced the German Aerospace Center's (DLR) custom-designed ultrasonic welding end-effector at the esteemed ITHEC 2018 conference held in Bremen. They presented their ongoing research on the continuous ultrasonic welding of carbon fiber reinforced Polyphenylenesulfide (PPS) and Polyetherketoneketone (PEKK), with a focus on potential robotic applications. [25] The DLR team further advanced their efforts to adapt the process for robotic applications (illustrated in Fig. 4), as demonstrated at the SAMPE 2019 conference in Nantes. Engelschall et al. presented initial findings, including the LSS of weld seam specimens, with values up to 25 MPa. Additionally, they presented the relationship between the consolidation pressure exerted by the consolidation unit (3) (illustrated in Fig. 2) and the welding force. [26]
Jongbloed et al. subsequently recognized the benefits of incorporating a consolidation unit into the continuous ultrasonic welding process, by analyzing the impact of its addition and removal. [27]
Jongbloed et al. investigated the differences and similarities between static and continuous ultrasonic welding processes, focusing on the combined effects of welding force and vibration amplitude, two key process parameters that significantly influence both applications. Their findings revealed that in static ultrasonic welding, the non-welded area at the weld interface decreases to zero when the vibration time is sufficient. In contrast, continuous ultrasonic welding results in a constant amount of un-molten and non-welded resin remaining underneath the sonotrode. To mitigate this limitation, either increasing the vibration amplitude or the welding force during continuous ultrasonic welding can be employed as a countermeasure. Additionally, their research revealed that the power required for continuous ultrasonic welding

is significantly higher, primarily due to the size of the semi-finished parts, such as the top and bottom adherends. Notably, their measurements provided insight into the temperature distribution, indicating that the heat-up phase at the interface commences prior to the sonotrode passing over the respective position, as a result of the entire adherends vibrating. [28]

Although Jongbloed et al. note a significant correlation between the optimal vibration time in static welding and the optimal welding speed in continuous welding, recent investigations highlight the importance of implementing active process control, particularly in continuous applications involving full-scale projects. This is necessitated by the need to account for variations in material stacking, weld seam irregularities, and fluctuations in material quality. Janek et al. have intensified DLR's efforts to develop active control strategies for the CUW process, as evidenced by their recent publication proposing an alternative power control mechanism that diverges from the conventional state-of-the-art amplitude control approach. The results indicate that the power control method exhibits enhanced responsiveness, albeit at the expense of reduced robustness. This finding suggests the potential for future cascaded control approaches that can leverage the distinct advantages of different control mechanisms. Notably, the investigation yielded peak LSS values of 48.4 MPa in amplitude-controlled welds, while the power-controlled welds achieved an reduced standard deviation of 6.3%, indicating improved process stability. [24]

Particularly, robotic ultrasonic welding has exhibited a surge in popularity as the understanding of its continuous utilization grows and the industry escalates its efforts in developing composite aircraft, composed of both thermoplastic and thermoset composites.

Recent advances in robotic ultrasonic welding, including the study conducted by Köhler in a joint effort between industry (CTC GmbH) and academia (TU Delft), have enhanced the comprehension of the interplay between process parameters like vibration amplitude, thickness of the energy director, and robot travel speed. Köhler and colleagues assessed the validity of their results by conducting welding and tensile testing on single lap shear specimens. Their analysis revealed a significant correlation between welding speed and weld seam quality, with slower speeds resulting in pronounced fiber distortion and faster speeds yielding a greater proportion of un-welded area. Notably, the vibration amplitude was found to have a significant impact on the thorough melting of the resin, with higher amplitudes resulting in more effectively molten weld interfaces. However, to mitigate the risk of overheating associated with high vibration amplitudes and their corresponding elevated heating rates, a proportional increase in welding speed is necessary. This increase in welding speed, in turn, reduces the overall consolidation period due to the limited consolidation length, ultimately yielding high porosity in rapidly produced welds. [29]

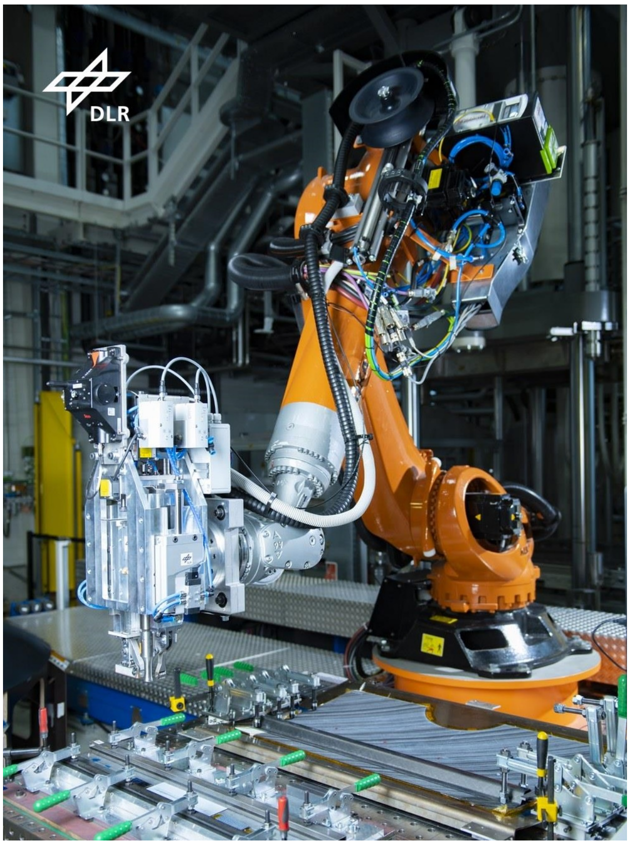

FIG 4. Robotic CUW with end-effector mounted to a KUKA robot. Image modified from [30].

A separate research team, led by Ahanpanjeh, conducted an in-depth examination of robotic ultrasonic welding, with a specific focus on the dynamic behavior of the robot and its correlation with the resulting weld trajectory. The researchers noted that the deflection of the robot, caused by the applied process forces, interacts with the inclination of the sonotrode, potentially influencing the quality of the weld. Additionally, a sensor-driven compensation methodology was implemented, resulting in enhanced weld trajectory accuracy. [31–33]

Previously, researchers at the DLR developed and introduced an innovative path-correction methodology, which integrates an edge-following mechanism, an active illumination subsystem, and a camera-based vision algorithm to achieve and maintain precise weld trajectories, as illustrated in Fig. 5. The Multi Functional Fuselage Demonstrator (MFFD) was one of the first and most significant full-scale projects to employ continuous ultrasonic welding, successfully completed by the DLR. As part of this project, 44 stringers were successfully welded to the upper skin of the composite fuselage demonstrator, utilizing the developed path correction methods during robotic CUW. [34]

A collaborative effort between the DLR and the National Research Council of Canada (NRC) led to the development of the next evolutionary advancement in robotic ultrasonic welding, facilitating the implementation of a dual-robot CUW application. The motivation behind developing a dual-robot application stems from the high costs associated with the specialized tools and jigs required for part production and assembly sequences. Specifically, in robotic ultrasonic welding, the need for a static anvil that accurately replicates the shape of the semi-finished parts can be prohibitively expensive, particularly during iterative part development phases. To address this challenge, the concept emerged to utilize a second robot to hold a movable anvil, which can mimic the actual structure to be supported by adjusting its trajectory accordingly. This approach was successfully demonstrated by welding a rear pressure bulkhead of a generic single-aisle aircraft. To simplify the tooling and jig requirements for the upstream Automated Fiber Placement (AFP) manufacturing process, the bulkhead was divided into eight identical segments. Upon conclusion of the welding process, eight bulkhead segments were successfully welded to two distinct half-pressure bulkheads. The subsequent two welds were abandoned due to an unforeseen interference between the supporting jig and the combined trajectories of the teaming robots. [35]

The ongoing efforts among international research groups indicate a significant shift towards the continuous application of ultrasonic welding, driven by the transfer of knowledge from static ultrasonic welding. Notably, the integration of robotics in this process presents novel challenges that necessitate in-depth investigation to ensure the delivery of high-quality outputs characterized by reliability and reproducibility.

4. MATERIALS

4.1. Thermoplasitc Composites

Currently, seven prominent thermoplastics are commonly employed: Polycarbonates (PC), Polyamides (PA), PPS, Polyetherimide (PEI), PEEK, PEKK and Low Melt Polyaryletherketone (LMPAEK). In the context of aerospace applications, thermoplastic composites primarily utilize PPS, PEI, PEEK, PEKK, and LMPAEK, which exhibit exceptional damage tolerance in their finished states. Additionally, these thermoplastic resins display excellent resistance to moisture and chemicals, thereby preventing degradation in hot and humid environments. [5, 36]

It is noteworthy that amorphous materials, such as PEI, and semi-crystalline materials, such as LMPAEK, display enhanced weldability due to their material properties when utilized in joining technologies like ultrasonic welding, particularly when compared to crystalline polymers. [8] The integration of fibrous reinforcements into thermoplastic matrices enables the development of composite materials, characterized by improved material attributes, such as an elevated strength-to-weight ratio, thus augmenting their mechanical efficacy. The preponderance of carbon fiber as the primary material in load-carrying airframe structures can be attributed to its superior mechanical properties. In contrast, aramid fibers exhibit limited applicability due to their hygroscopic nature, which renders them susceptible to moisture-induced degradation. Glass fibers, while possessing notable tensile strength and economic viability, are characterized by a significant reduction in stiffness (approximately 3-4 times) compared to carbon fibers. Furthermore, their increased density negates their potential for lightweight design, thereby limiting their utilization in modern civil aircraft to a select few components. [4]

4.2. Hybrid Composites

Thermoplastic composites exhibit advantageous properties, including ductility, weldability, and thermoforming capabilities, thereby enhancing the potential for automation and optimizing the manufacturing efficiency ratio. Notwithstanding their advantages, thermoplastic composites also possess inherent limitations, notably diminished thermal resistance resulting from the absence of intermolecular chemical crosslinks. This lack of crosslinking also compromises their creep and relaxation behavior, rendering it inferior to that of thermoset composites. While thermoset composites possess their own set of property limitations, their duromeric characteristics can mitigate some of the drawbacks associated with thermoplastic composites, thereby providing a complementary set of properties. [37]

As researchers continue to push the boundaries of composite materials, it is becoming increasingly likely that future aerospace applications will rely on hybrid compositions that combine the benefits of both thermoplastic and thermoset composites. A study by Villegas and van Moorleghem has already demonstrated the feasibility of ultrasonic welding of hybrid composite joints. By incorporating a thermoplastic PEI layer into the composite, which is co-consolidated with the thermoset adherend, the researchers were able to impart weldability to the epoxy-based composite, paving the way for the development of innovative hybrid materials that can meet the demanding requirements of the aerospace industry. [38]

Hence, the prospective implementation of ultrasonic welding technology will encounter the intricate challenge of integrating diverse polymeric materials, thereby underscoring the imperative for a comprehensive elucidation of the thermal mechanisms underlying ultrasonic welding and the subsequent solidification phenomena occurring during the consolidation phase.

5. STAKEHOLDERS

Identification of stakeholders potentially impacted by the introduction of a new technology is facilitated through analysis of the most recently affected stakeholder, the approval and certification agencies. By examining the approval criteria pertinent to aircraft design and manufacturing, it is possible to discern the relevant domains of interest and their corresponding interfaces. To achieve this, an initial analysis of the respective authorities is conducted.

5.1. Certification

The primary goal of commercial aircraft manufacturers, such as Airbus and Boeing, is the design, fabrication, and regulatory certification of aerostructures that correspond to their intended aircraft applications. Consequently, certification agencies are a crucial stakeholder, as they play a pivotal role in the certification and validation of aircraft systems. The European Union Aviation Safety Agency (EASA), Federal Aviation Administration (FAA), Agência Nacional de Aviação (ANAC) and Transport Canada Civil Aviation (TCCA) have joined forces and established a certification management team in order to synchronize common efforts under bilateral agreements. Therefore, EASA certification regulations, as mentioned hereafter, are applicable to the other certification authorities at a similar extent. [39]
The EASA issues Certification Specifications (CS) as a set of regulations and Acceptable Means of Compliance (AMC), which can serve as a primary reference for the certification and validation of the airworthiness of products, parts, and appliances. The general AMC-20-29 offers guidance specifically for composite aircraft structures (primarily carbon or glass fiber composites), that relate to further stakeholders, such as design, stress, production and quality assurance of the materials and processes used. [40, 41]
The EASA does not certify any materials or processes directly, however the specifications for materials and processes are part of the type-design that falls under the type-certification of an aircraft. [40]
Hence, the Agency provides AMC to show compliance with the appropriate CS in respect to material quality traceability, production facility arrangements, design data, tolerance management, stress and damage tolerance analysis, environmental conditions and destructive as well as non-destructive testing to ensure a reproducible and reliable product, with proven quality for the initial and continuous airworthiness of the aircraft. [40, 41]

5.2. Design

Established design guidelines provide methodologies for conducting a structured development and design process. These guidelines identify the description and definition of functions that the product is intended to perform as one of the most important steps. The consistent elaboration at the functional level ensures a deep understanding of the necessary product and system requirements that must be met in order to fulfill these functions. [4]
The primary function of ultrasonically welded joints is to achieve proper bonding between individual parts or sub-assemblies in a specific location, within certain specified limitations. According to EASA, this generic and abstract function must be performed in a reliable, robust, and reproducible manner within certain prescribed tolerance limits. Knowledge regarding tolerances, including material tolerances, processing tolerances, and assembly tolerances, can be established through analysis supported by appropriate tests conducted at the coupon, element, and sub-component levels. Allowable tolerances are determined based on design values and are further refined through coupon testing as well as sub-component testing during the qualification phase. Consequently, the overall tolerances for the product must be specified in the design documentation (such as drawings) to ensure that the final product remains within the intended and qualified range defined by the design service goal. [4, 40]
Another secondary consideration in the design phase is manufacturing-related defects, which can arise from improper application procedures or the accidental dropping of tools. Therefore, it is essential to anticipate such possibilities by incorporating appropriate tolerances into the design. [4]
Additionally, manufacturing-related boundary conditions must also be taken into account when designing individual components and determining the sequence of assembly processes. True-scale projects, such as the MFFD, have highlighted that the working space and reach of the robot may not always correspond to the intended and required specifications. It is crucial to ensure that the accessibility of the robot's end-effector is guaranteed, so that the ultrasonic welding operations can be successfully carried out without any interference from potential collisions with the airframe structure or surrounding infrastructure. Hence, a dedicated tool space allocation should be derived from the tool design and robot trajectory data.

5.3. Stress and Fatigue

When evaluating the static strength of composite materials, it is crucial to consider all critical load cases, failure modes, and environmental effects, including residual stresses, material variability, and defects. A program of component ultimate load tests in the relevant environment is necessary to demonstrate static strength, unless prior experience with similar designs and materials can validate analysis supported by sub-component and coupon tests. [40]
EASA recommends a hierarchical testing approach ('building block' see Fig. 6), where a large number of low-level tests (coupons and elements) are used to establish a statistical basis and gather knowledge. This information is then applied to more complex sub-component and main component tests, mitigating the risk of failure in costly and time-consuming full-scale tests that typically occur later in the development process, refer to Fig. 6. [40]
Consequently, lap shear stiffness and strength tests are commonly employed to evaluate the mechanical properties of adhesives and bonding processes for qualification purposes. However, shear tests have been found to be inadequate for assessing

long-term durability and environmental degradation resulting from suboptimal bonding processes, such as inadequate adhesion. In contrast, peel tests have demonstrated greater reliability in evaluating the efficacy of adhesion. [40, 42–44] Moreover, airframe structures must demonstrate robust fatigue life beyond their intended service duration, in addition to static loads. Assessments are necessary to validate that catastrophic failures resulting from fatigue, environmental degradation, manufacturing flaws, or accidental impacts will not transpire or compromise safe operation. [40] Fatigue validation must be achieved via component tests or analysis corroborated by test data, considering relevant environmental effects. Test articles, produced and assembled per production standards, must replicate production structures. Adequate testing of components, sub-components, or coupons is required to determine fatigue scatter and environmental influences. Impact damage and other permissible defects should be included in fatigue testing. Throughout its anticipated lifespan, the product should demonstrate that its stiffness properties remain within satisfactory bounds, as indicated by fatigue assessments. [40] Therefore, ultrasonic welding must be qualified to consistently produce weld spots or seams with sufficient strength to withstand static and cyclic loads that correspond to those experienced by the respective aircraft and envelope of loads.

5.4. Production and Automation

An additional critical factor and related stakeholder is the automation of manufacturing and the up-scaling of the process to accommodate full-scale airframe structures. In accordance with EASA regulations, certification credit may be awarded to products and organizations that employ identical materials and processes in comparable applications, provided that such credit is duly substantiated and applicable. This principle extends beyond mere facility-level variables, such as ambient temperature, humidity, and site cleanliness or the sourcing and qualification of raw materials; it also encompasses the entirety of the manufacturing workflow, its precise execution, and the seamless exchange of process data among machines, whether housed within a single plant or distributed across geographically disparate sites. [40]
Robotic implementations that must contend with relatively large process forces are intrinsically susceptible to performance penalties, most notably diminished positional accuracy arising from the elastic compliance of the robot's structure. [45, 46]
Initial demonstrations of a robust and reproducible robotic ultrasonic welding system were carried out within the MFFD project in 2023. In the same period, DLR introduced a novel path-correction methodology that employs an edge-following mechanism, an active illumination subsystem, and a camera-based vision algorithm to maintain precise weld trajectories as displayed in Fig. 5. [34]

Another methodology has been introduced by Ahanpanjeh et al. in a recent publication, which leverages a sensor-based trajectory correction system. Analogous to the aforementioned camera-vision based methodology, this approach aims to enhance process robustness by ensuring accurate path execution of the robot during the welding operation. [33]
The accuracy of robotic movement is a critical factor that can significantly impact the reliability of automated, robot-assisted welding processes. [45] Recent studies, such as those conducted by Brandt et al. using the AFPprocess, have highlighted the potential benefits of implementing correction algorithms to enhance robotic accuracy. [35] Furthermore, the integration of machine learning and deep learning algorithms offers promising opportunities to improve the precision of robotic movements, minimize deviations, to potentially optimize the overall quality of the welding process. [47] This, in turn, could lead to more robust and reproducible results. Ongoing research at the German Aerospace Center is currently exploring the application of this innovative technology in the field of ultrasonic welding, with a focus on investigating its potential to enhance the reliability and efficiency of this process.

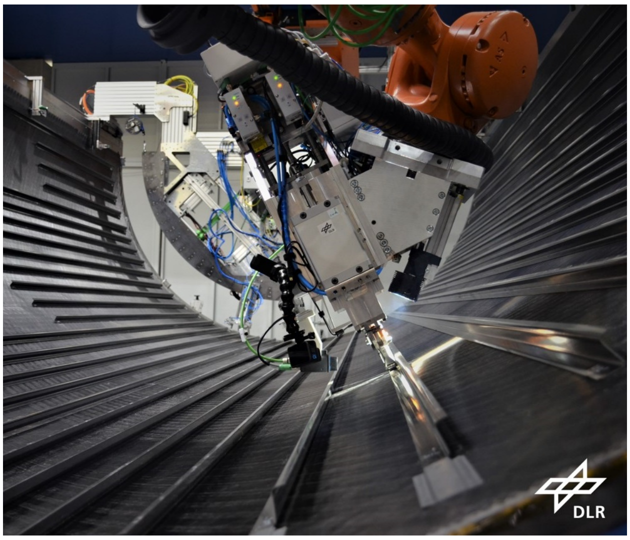

FIG 5. Path correction of welding seam track during robotic ultrasonic welding on the Multi Functional Fuselage Demonstrator at DLR in 2023. Image modified from [34].

5.5. Quality and NDT

In service, bond failures and corresponding issues have been attributed to insufficient qualifications and inadequate quality control in production processes [40]. Hence, requirements as governed by CS 23.573 are established for primary composite airframe structures, including considerations for damage tolerance, fatigue, and bonded joints. [41]
While it is true that certain non-inspectable end items, primarily critical structural details, must undergo destructive inspection and testing to gain knowledge

about manufacturing flaws and ensure reliable fabrication through process control, EASA emphasizes the importance of repeatable and reliable non-destructive inspection techniques. These techniques are imperative for ensuring the quality and strength of each joint. [40]

Non-Destructive Testing (NDT) encompasses a diverse range of methodologies, including mechanical vibration analysis, ultrasonic emission-based acoustic testing, high-resolution radiographic imaging via X-ray computed tomography, electrical conductivity evaluation through eddy current analysis, and thermal radiation assessment employing vibration-induced thermography. [4]

Ultrasonic testing is commonly employed to identify defects such as delamination, foreign body inclusions, and porosity in various materials. [4] Notably, Janek et al. have shown the efficacy of water-coupled ultrasonics for quality assessment in their study on alternative process control methodologies for ultrasonic welding, highlighting the potential of this non-destructive testing technique for evaluating material integrity. [24] Furthermore, EASA recommends to specify and monitor key characteristics and processing parameters for an in-situ quality control during process operation. [40]

The work of Görick et al. has demonstrated the tremendous potential of utilizing inline-quality control mechanisms and gathering weld seam quality-related data, specifically highlighting the expressiveness of process data such as thermal radiation and sound data. This approach can be further enhanced through the incorporation of post-processing mechanisms, such as quality prediction through machine learning algorithms. This novel approach to non-destructive testing has the potential to be applied not only to inspectable items but also to non-inspectable areas of the weld seam. [48–51]

6. TECHNOLOGY READINESS

In the previous chapters, stakeholders of a new technology, such as ultrasonic welding, were introduced in order to create a structured roadmap. Additionally, EASA provides a conceptual framework in the form of a block diagram to inform the development of a comprehensive test program. This program aims to generate a robust knowledge base and data repository, thereby facilitating the characterization and optimization of materials and manufacturing processes required for the fabrication of the intended airframe structure. Such knowledge is built through testing diverse non-generic and generic test specimens in order to demonstrate compliance with the associated Technology Readiness Level (TRL), see Fig. 6. [5,40]

As discussed in chapter 3. significant efforts have been dedicated to advancing the ultrasonic welding technology, with a primary focus on generic coupon-level development. Additionally, preliminary attempts have been made to scale up the technology by adapting the process for robotic applications and real-scale projects. Nevertheless, a comprehensive transition from TRL1 to TRL6 has yet to be demonstrated in open literature, although unpublished and confidential industry reports may exist.

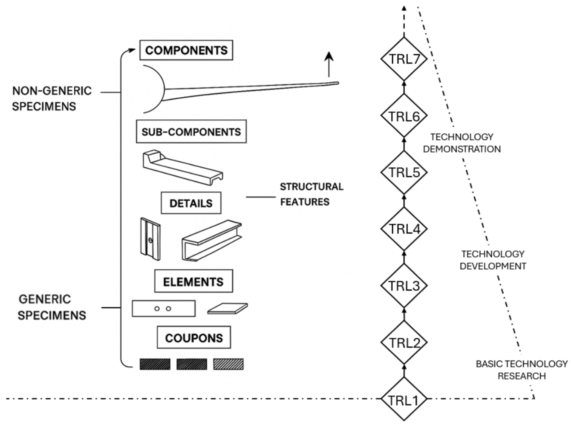

FIG 6. Building block approach from generic coupon level towards non-generic main component according to EASA, incorporating TRLs appropriately. Image inspired by [4], [5] and [40].

7. SUMMARY

The ultrasonic welding process demonstrates potential as an effective joining technology for the fabrication of high-performance structural components, particularly in the aviation industry, where its elevated level of automation can be advantageous. According to academia and research institutes, the ultrasonic welding process exhibits the capability to generate high-quality spot welds and weld seams via both static and continuous operation modes. Notwithstanding the demonstrated robotic scalability and high-quality weld seam attributes, including satisfactory LSS properties, as evidenced in the MFFD project and corroborated by multiple scientific studies, the process remains under comprehensive development and refinement to achieve full technological maturity across all readiness levels. According to EASA regulations and the individual Certification Plan, manufacturers are responsible for qualifying materials and manufacturing processes, which involves demonstrating their suitability at a TRL 3 through the use of generic geometries of test coupons. However, the final qualification of components is conducted on non-generic geometries specific to the actual components. Given this disparity, it is essential to involve aircraft manufacturers throughout the development process, from initial stages to final qualification. This is because manufacturers possess unique knowledge of the final component and assembly geometries, as well as the materials and composite stacking used. While the ultimate accountability for implementing advancements in aircraft manufacturing rests with the manufacturers themselves, achieving significant progress necessitates a collaborative effort between academic institutions and industrial entities. This partnership is crucial for successfully transitioning the technology from a laboratory setting to a practical application in the manufacturing environment, specifically from TRL 3 to TRL 6 and beyond. Research institutions, including the *SAM XL Engineering* in the Netherlands, the *Composite Technology Center* in Stade, and the German Aerospace Center's *Institute of Structures and Design*, are well-positioned to lay the groundwork for the successful transfer of knowledge and technology to the industrial sector. This fundamental basis is crucial for ensuring the effective adoption and implementation of the ultrasonic welding process.

Contact address:

maximilian.janek@dlr.de

References

[1] Stefan Gössling and Andreas Humpe. The global scale, distribution and growth of aviation: Implications for climate change. *Global Environmental Change*, 65:102194, Nov. 2020. ISSN: 0959-3780. DOI: 10.1016/j.gloenvcha.2020.102194.

[2] International Civil Aviation Organization. Carbon offsetting and reduction scheme for international aviation (CORSIA). online. Accessed: 01.09.2025. https://www.icao.int/CORSIA.

[3] International Civil Aviation Organization. CORSIA 2020 emissions. Tech Report No.2, ICAO, Oct. 2022.

[4] Ulf Paul Breuer. *Commercial Aircraft Composite Technology*. Springer eBook Collection. Springer, Cham, 2016. ISBN: 9783319319186.

[5] Lars Larsen, Manuel Endrass, Stefan Jarka, Simon Bauer, and Maximilian Janek. Exploring ultrasonic and resistance welding for thermoplastic composite structures: Process development and application potential. *Composites Part B: Engineering*, 289:111927, Jan. 2025. ISSN: 1359-8368. DOI: 10.1016/j.compositesb.2024.111927.

[6] Irene Fernandez Villegas. Ultrasonic welding of thermoplastic composites. *Frontiers in Materials*, 6, Nov. 2019. ISSN: 2296-8016. DOI: 10.3389/fmats.2019.00291.

[7] Jiaming Liu, Dong Quan, Gennaro Scarselli, Rene Alderliesten, Hao Wang, and Guoqun Zhao. Developments and future prospects of welding technology for carbon fiber thermoplastic composites. *Composites Part B: Engineering*, 297:112314, May 2025. ISSN: 1359-8368. DOI: 10.1016/j.compositesb.2025.112314.

[8] Ali Yousefpour, Mehdi Hojjati, and Jean-Pierre Immarigeon. Fusion bonding/welding of thermoplastic composites. *Journal of Thermoplastic Composite Materials*, 17(4):303–341, July 2004. ISSN: 1530-7980. DOI: 10.1177/0892705704045187.

[9] Somen K. Bhudolia, Goram Gohel, Kah Fai Leong, and Aminul Islam. Advances in ultrasonic welding of thermoplastic composites: A review. volume 13, page 1284. MDPI AG, Mar. 2020. DOI: 10.3390/ma13061284.

[10] Avraham Benatar and Timothy G. Gutowski. Ultrasonic welding of peek graphite apc□2 composites. *Polymer Engineering and Science*, 29(23):1705–1721, Dec. 1989. ISSN: 1548-2634. DOI: 10.1002/pen.760292313.

[11] I. F. Villegas, B. V. Grande, H. E. N. Bersee, and R. Benedictus. A comparative evaluation between flat and traditional energy directors for ultrasonic welding of thermoplastic composites. Seville, Spain, June 2014. ECCM16, 16th European Conference on Composite Materials.

[12] Avraham Benatar, Raman V. Eswaran, and Satinder K. Nayar. Ultrasonic welding of thermoplastics in the near□field. *Polymer Engineering amp; Science*, 29(23):1689–1698, Dec. 1989. ISSN: 1548-2634. DOI: 10.1002/pen.760292311.

[13] Avraham Benatar and Zhang Cheng. Ultrasonic welding of thermoplastics in the far-field. *Polymer Engineering and Science*, 29(23):1699–1704, Dec. 1989. ISSN: 1548-2634. DOI: 10.1002/pen.760292312.

[14] G. Kempe and G. Korger-Roth. Ultraschallschweißen von carbonfaserverstärktem PEEK. *Interner Bericht - Insitut für Bauweisen und Konstruktionsforschung DLR Stuttgart*, 1994.

[15] Tian Zhao, Charlotte Broek, Genevieve Palardy, Irene Fernandez Villegas, and Rinze Benedictus. Towards robust sequential ultrasonic spot welding of thermoplastic composites: Welding process control strategy for consistent weld quality. *Composites Part A: Applied Science and Manufacturing*, 109:355–367, June 2018. ISSN: 1359-835X. DOI: 10.1016/j.compositesa.2018.03.024.

[16] Tian Zhao, Calvin Rans, Irene Fernandez Villegas, and Rinze Benedictus. On sequential ultrasonic spot welding as an alternative to mechanical fastening in thermoplastic composite assemblies: A study on single-column multi-row single-lap shear joints. *Composites Part A: Applied Science and Manufacturing*, 120:1–11, May 2019. ISSN: 1359-835X. DOI: 10.1016/j.compositesa.2019.02.013.

[17] Irene Fernandez Villegas and Harald E. N. Bersee. Ultrasonic welding of advanced thermoplastic composites: An investigation on energy-

directing surfaces. *Advances in Polymer Technology*, 29(2):112–121, June 2010. ISSN: 1098-2329. DOI: 10.1002/adv.20178.

[18] Irene Fernandez Villegas. Strength development versus process data in ultrasonic welding of thermoplastic composites with flat energy directors and its application to the definition of optimum processing parameters. *Composites Part A: Applied Science and Manufacturing*, 65:27–37, Oct. 2014. ISSN: 1359-835X. DOI: 10.1016/j.compositesa.2014.05.019.

[19] Wang Tao, Xuan Su, Haohan Wang, Zenghuan Zhang, Hao Li, and Jie Chen. Influence mechanism of welding time and energy director to the thermoplastic composite joints by ultrasonic welding. *Journal of Manufacturing Processes*, 37:196–202, Jan. 2019. ISSN: 1526-6125. DOI: 10.1016/j.jmapro.2018.11.002.

[20] Eirini Tsiangou, Sofia Teixeira de Freitas, Irene Fernandez Villegas, and Rinze Benedictus. Investigation on energy director-less ultrasonic welding of polyetherimide (PEI)- to epoxy-based composites. *Composites Part B: Engineering*, 173:107014, Sept. 2019. ISSN: 1359-8368. DOI: 10.1016/j.compositesb.2019.107014.

[21] Irene Fernandez Villegas. In situ monitoring of ultrasonic welding of thermoplastic composites through power and displacement data. *Journal of Thermoplastic Composite Materials*, 28(1):66–85, Feb. 2013. ISSN: 1530-7980. DOI: 10.1177/0892705712475015.

[22] Tian Zhao, Quanyue Zhao, Wenwang Wu, Li Xi, Ying Li, Zhishuai Wan, Irene Fernandez Villegas, and Rinze Benedictus. Enhancing weld attributes in ultrasonic spot welding of carbon fibre-reinforced thermoplastic composites: Effect of sonotrode configurations and process control. *Composites Part B: Engineering*, 211:108648, Apr. 2021. ISSN: 1359-8368. DOI: 10.1016/j.compositesb.2021.108648.

[23] N. Koutras, R. Benedictus, and I. Fernandez Villegas. Thermal effects on the performance of ultrasonically welded cf/pps joints and its correlation to the degree of crystallinity at the weldline. *Composites Part C: Open Access*, 4:100093, Mar. 2021. ISSN: 2666-6820. DOI: 10.1016/j.jcomc.2020.100093.

[24] Maximilian Janek, Dominik Görick, Lars Larsen, Stefan Jarka, and Michael Kupke. Investigation of power and amplitude control in continuous ultrasonic welding of unidirectional CFRPs: A comparative study. *Composites Part A: Applied Science and Manufacturing*, page 109194, Aug. 2025. ISSN: 1359-835X. DOI: 10.1016/j.compositesa.2025.109194.

[25] M. Engelschall, S. Jarka, F. Fischer, M. Willmeroth, and L. Larsen. Development of continuous ultrasonic welding for the automated production of aircraft primary structures. volume 4th, Bremen, Germany, 2018. ITHEC 2018, ITHEC 2018, International Conference and Exhibition on Thermoplastic Composites.

[26] M. Engelschall, L. Larsen, F. J. C. Fischer, and M. Kupke. Robot-based continous ultrasonic welding for automated production of aerospace structures. SAMPE Europe Conference 2019 Nantes, 2019.

[27] Bram Jongbloed, Rahul Vinod, Julie Teuwen, Rinze Benedictus, and Irene Fernandez Villegas. Improving the quality of continuous ultrasonically welded thermoplastic composite joints by adding a consolidator to the welding setup. *Composites Part A: Applied Science and Manufacturing*, 155:106808, Apr. 2022. ISSN: 1359-835X. DOI: 10.1016/j.compositesa.2022.106808.

[28] Bram Jongbloed, Julie Teuwen, Rinze Benedictus, and Irene Fernandez Villegas. On differences and similarities between static and continuous ultrasonic welding of thermoplastic composites. *Composites Part B: Engineering*, 203:108466, Dec. 2020. ISSN: 1359-8368. DOI: 10.1016/j.compositesb.2020.108466.

[29] Filipp Köhler, Irene Fernandez Villegas, Clemens Dransfeld, and Axel Herrmann. On the influence of welding parameters and their interdependence during robotic continuous ultrasonic welding of carbon fibre reinforced thermoplastics. *Materials*, 17(21):5282, Oct. 2024. ISSN: 1996-1944. DOI: 10.3390/ma17215282.

[30] Deutsches Zentrum für Luft-und Raumfahrt e.V. Ultrasonic welding. https://www.dlr.de/en/zlp/about-us/the-institute/site-augsburg/ultrasonic-welding, 2017. Accessed: 2025-05-29.

[31] Maryam Ahanpanjeh, Filipp Köhler, Vincent Adomat, Christian Kober, Marc Fette, and Jens Wulfsberg. Impact of alignment of the sonotrode on the quality of thermoplastic composite joints in continuous ultrasonic welding. 11 2022. SAMPE 22 Hamburg.

[32] Maryam Ahanpanjeh, Marc Fette, and J Wulfsberg. Moving towards robotic ultrasonic welding of complex composites structures: Robotics, in-situ monitoring and digitalisation. pages 207–210, 10 2024.

[33] Maryam Ahanpanjeh, Jannis Eckhoff, Marc Fette, Alexander Fay, and Jens. P. Wulfsberg. Improving robotic continuous ultrasonic welding performance through sensor-driven path correction. In *2025 11th International Conference on Control, Automation and Robotics*

(ICCAR), pages 225–231. IEEE, Apr. 2025. DOI: 10.1109/iccar64901.2025.11073066.

[34] York C. Roth, Ralf Herrmann, Cristina Sanchez Santos, Matthias Uellendahl, Joost Koopman, Andreas Henneberg, Johan Kos, Irene F. Villegas, Abhas Choudhary, Lars Larsen, Stefan Ferstl, Benjamin Diehl, Frida Emanuelsson, Jean Benoit Sinéchal, Matthieu Pleth, and Kathryn Atherton. Cleansky2/ Clean Aviation Large Passenger Aircraft for More Sustainable Commercial Fuselage Technologies–Major Achievements. *ICAS Proceedings*, 2:3–22, 2024. ISSN: 29584647.

[35] L. Brandt, M. Vistein, D. Deden, P. Gänswürger, M. Janek, L. Larsen, J-M. Audet, G. Côté, and B. Monsarrat. Tool- and jigless production of thermoplastic CFRPs based on cooperating robots. SAMPE Europe Conference 2024 Belfast, 2024.

[36] Ronald Krueger and Andrew Bergan. Advances in Thermoplastic Composites Over Three Decades - A Literature Review. Technical Report NASA/TM-20240005376, National Aeronautics and Space Administration (NASA), Hampton, Virginia, USA, May 2024.

[37] Michel Biron, editor. *Thermoplastics and thermoplastic composites*. Plastics design library. William Andrew, Amsterdam, 2nd ed edition, 2013. ISBN: 9781455778980. Includes index. - Description based on title from publisher's website; (ScienceDirect; viewed on Oct. 31, 2012).

[38] Irene Fernandez Villegas and Regis van Moorleghem. Ultrasonic welding of carbon/epoxy and carbon/peek composites through a PEI thermoplastic coupling layer. *Composites Part A: Applied Science and Manufacturing*, 109:75–83, June 2018. ISSN: 1359-835X. DOI: 10.1016/j.compositesa.2018.02.022.

[39] European Union Aviation Safety Agency. Bilateral agreements - Certification Management Team. https://www.easa.europa.eu/en/document-library/bilateral-agreements, 2015. Accessed: 2025-09-03.

[40] European Union Aviation Safety Agency. General Acceptable Means of Compliance for Airworthiness of Products, Parts and Appliances(amc-20). Technical Report Amendment 23, EASA, Cologne, Germany, Jan. 2022.

[41] European Union Aviation Safety Agency. Certification Specifications and Acceptable Means of Compliance for Large Aeroplanes (CS-25). Technical Report Amendment 28, EASA, Cologne, Germany, Dec. 2023.

[42] ASTM International. Standard Test Method for Apparent Shear Strength of Single-Lap-Joint Adhesively Bonded Metal Specimens by Tension Loading (Metal to Metal), 2005. Issued: 2005-07.

[43] AIRBUS. Determination of Tensile Lap Shear Strength of Composite Joints, 2015. Issued: 2015-06.

[44] AIRBUS. Determination of mode I fracture toughness energy of bonded joints (G_{1c} Test), 2015. Issued: 2015-11.

[45] Yin Bu, Wenhe Liao, Wei Tian, Jin Zhang, and Lin Zhang. Stiffness analysis and optimization in robotic drilling application. *Precision Engineering*, 49:388–400, July 2017. ISSN: 0141-6359. DOI: 10.1016/j.precisioneng.2017.04.001.

[46] Biao Mei and Weidong Zhu. Accurate positioning of a drilling and riveting cell for aircraft assembly. *Robotics and Computer-Integrated Manufacturing*, 69:102112, June 2021. ISSN: 0736-5845. DOI: 10.1016/j.rcim.2020.102112.

[47] Ali Maghami, Alaïs Imbert, Gabriel Côté, Bruno Monsarrat, Lionel Birglen, and Matt Khoshdarregi. Calibration of multi-robot cooperative systems using deep neural networks. *Journal of Intelligent amp; Robotic Systems*, 107(4), Apr. 2023. ISSN: 1573-0409. DOI: 10.1007/s10846-023-01867-6.

[48] D. Görick, L. Larsen, M. Engelschall, and A. Schuster. Quality prediction of continuous ultrasonic welded seams of high-performance thermoplastic composites by means of artificial intelligence. *Procedia Manufacturing*, 55:116–123, 2021. ISSN: 2351-9789. DOI: 10.1016/j.promfg.2021.10.017.

[49] Dominik Görick, Alfons Schuster, Lars Larsen, Jonas Welsch, Tobias Karrasch, and Michael Kupke. New input factors for machine learning approaches to predict the weld quality of ultrasonically welded thermoplastic composite materials. *Journal of Manufacturing and Materials Processing*, 7(5):154, Aug. 2023. ISSN: 2504-4494. DOI: 10.3390/jmmp7050154.

[50] Dominik Görick, Lars Larsen, Isabelle Stingl, Dirk Baumbach, and Alfons Schuster. The use of thermal data for quality assurance in the process of continuous ultrasonic welding of thermoplastic composite materials. *e-Journal of Nondestructive Testing*, 29(6), June 2024. ISSN: 1435-4934. DOI: 10.58286/29934.

[51] Dominik Görick, Jonas Welsch, Carlos D. Gerardo, Michael Kupke, Edmond Cretu, and Robert Rohling. Inline monitoring of continous ultrasonic welding processes of thermoplastic composites via a custom polycmut based ultrasound array. *e-Journal of Nondestructive Testing*, 29(6), June 2024. ISSN: 1435-4934. DOI: 10.58286/29933.