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Jig-less end-effector system for automating exhausting composite fuselage assembly tasks

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Abstract. In this study, the jig-less end-effector system developed to assemble components of a full-scale multifunctional integrated composite thermoplastic lower fuselage section is tested and validated. To offset the environmental impact of higher volume of air transport, the aviation industry wants to design lighter and more environmentally friendly aircraft. To achieve this, there is a need to exploit novel materials and technologies. Advanced thermoplastic composites provide an excellent material option thanks to their weldability, low density, low overall production cost, improved fracture toughness and recyclability. However, to fully appreciate their capabilities and benefits, new manufacturing approaches and techniques are needed. Hence, projects such as TCTool, “innovative tooling, end-effector development and industrialisation for welding of thermoplastic components”, aim to develop innovative tooling and end-effector systems for the assembly of a multifunctional thermoplastic fuselage. This study presents the development, operation, and testing of the jig-less end-effector system used in the TCTool project for picking, placing, and temporary welding and fixing fuselage’s clips and stringers.

Keywords: Thermoplastic; Composites; Aerospace; Automation; End-effector; Manufacturing.

1. Introduction

Studies acknowledge that the aviation sector is a significant contributor to climate change; it is also acknowledged that the current rate of air travel growth presents a real challenge to how fast the aerospace industry can become greener, being one of the hardest sectors to achieve greenhouse gas emission reductions [1-3]. One issue that limits the opportunities to further improve the fuel efficiency of aviation's is the slow uptake of innovations [4].

The latest European Aviation Environmental Report states that improving the environmental performance of the aviation sector requires effective coordination between stakeholders; this should build on existing measures and address the environmental challenges, thus ensuring the long-term success of the aviation sector [5].



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Substantial investments in innovative technologies are ongoing to offset aviation's emissions. One of which is STUNNING programme led by Airbus. STUNNING [6] (Smart Multi-Functional and Integrated Thermoplastic Fuselage) is set to deliver a double-digit fuel burn reduction for the Large Passenger Aircraft (LPA). Programme's target is to validate high potential combinations of innovations within multifunctional thermoplastic fuselage airframe structure. This multifunctional fuselage demonstrator employs advanced materials and applies innovative design principles combined with the most advanced system architecture for the next generation cabin [7, 8].

As a project within STUNNING programme, TCTool [9] (Innovative Tooling, End-Effector Development and Industrialisation for Welding of Thermoplastic Components) aims the development of innovative tooling and end-effector systems for the assembly of the multifunctional thermoplastic fuselage [7]. This study presents the development and validation of the tooling required to assemble the exhausting composite fuselage components, clips and stringers.

2. Components assembly

The scope of the TCTool project is limited to the structural components in the lower half of the asymmetrical aircraft fuselage, having a contour similar to the Airbus single-aisle line [10]. This section has a length of 8m, and 2 to 2.5m radius. The jig-less end-effector system, designed by Advanced Center for Aerospace Technologies (CATEC) [11], aims to assemble three components together: Thickness-varying composite fuselage skin, composite stringers, and composite frame clips. In which, the skin will be strengthened by 38 stiffening thermoplastic omega-stringer, and a sum of 206 clips will transfer the load from the internal components of the stiffened fuselage. Further details of these components can be obtained from the STUNNING project [6] and the work reported by Veldman et al. [8]. The role of the end-effector is to pick, place and temporarily fix these components in place until permanent joining takes place, as seen in Figure 1.

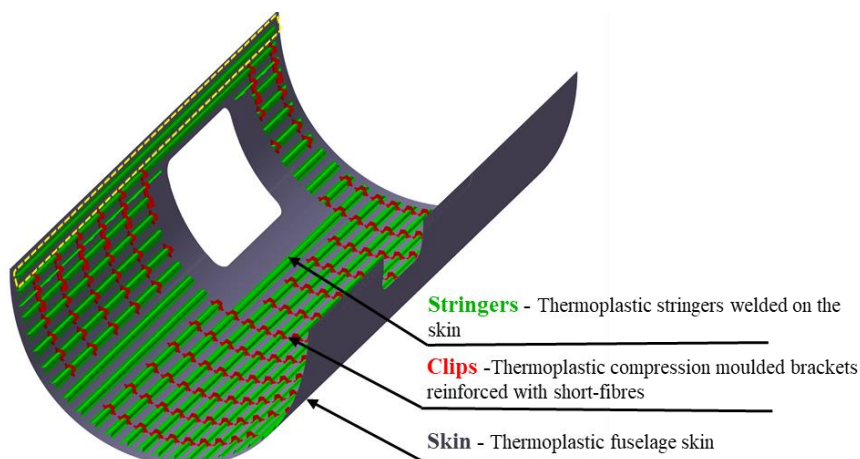


Figure 1. The key structural components of the multifunctional fuselage demonstrator that will be assembled by the jig-less end-effector system.

3. The Jig-less end-effector system

Although thermoplastic components can address the cure cycle roadblock that slows down thermoset parts production because their linear polymer chains do not crosslink and do not require a cure cycle [12]. However, there is a need to develop innovative assembly systems aligned with components supply chain production rate. Therefore, developing this end-effector system aims to demonstrate industrial scalability and integration to increase the production rate by automating exhausting assembly tasks, namely stringers and clips assembly.

Specifically related to the assembly of these components, three main challenges drove the development of the jig-less end-effector, as shown in Figure 2.

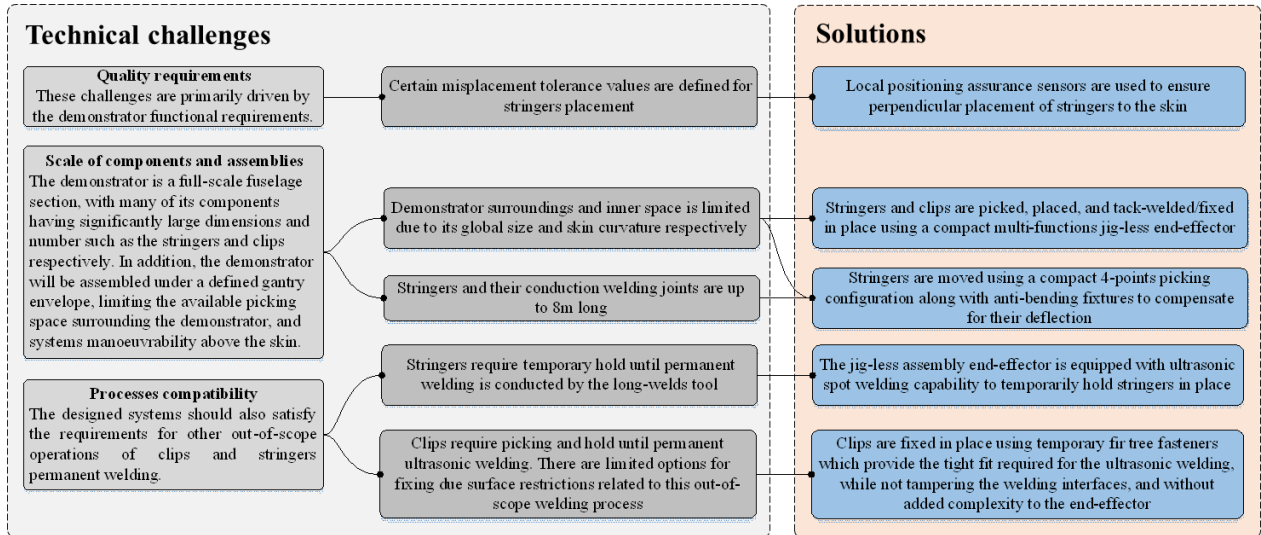


Figure 2. An illustration of the key technical design drives and the corresponding solutions.

Positioning stringers and clips accurately is a critical and exhausting step for manufacturing aircraft fuselage due to their quantity and function. Therefore, the developed jig-less assembly end-effector integrated several systems to conduct two main activities: picking and placing both stringers and clips. These developed systems are reported in a previous study for the TCTool project, which are: positioning assurance, stringer picking and placing system, stringers anti-bending fixtures, stringers tack-welding, clips picking and temporary fix, see Figure 3. And the process in which these systems are utilised for the picking, placing, and temporary fixing stringers and clips is illustrated in the flow diagram shown in Figure 4.

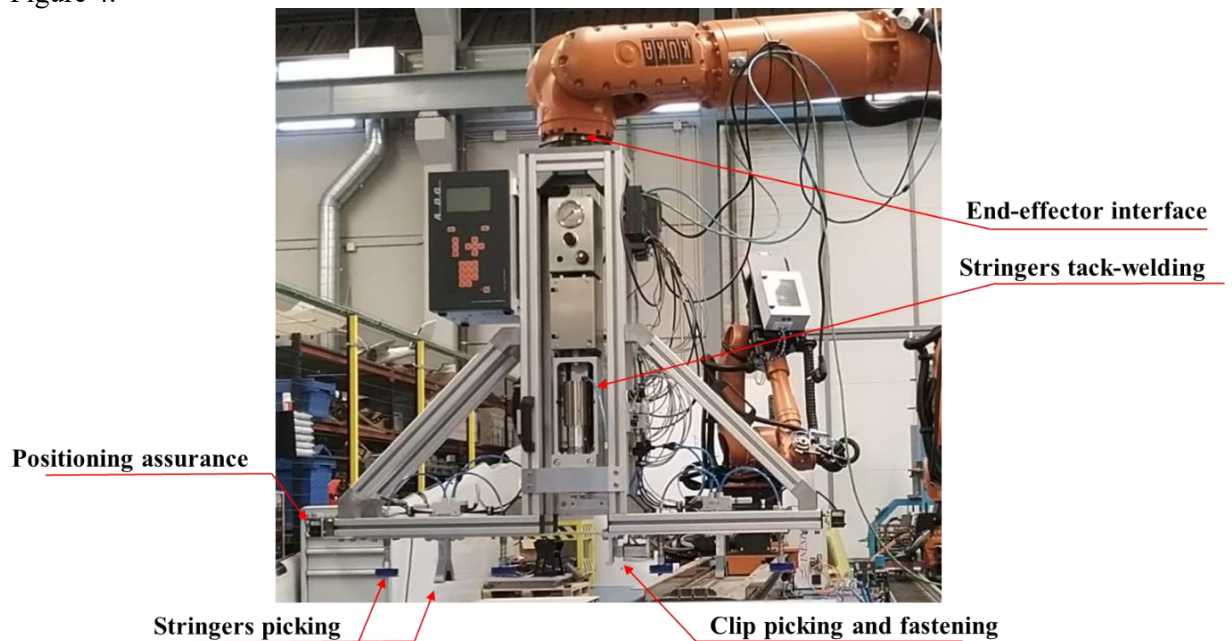


Figure 3. The manufactured jig-less assembly end-effector.

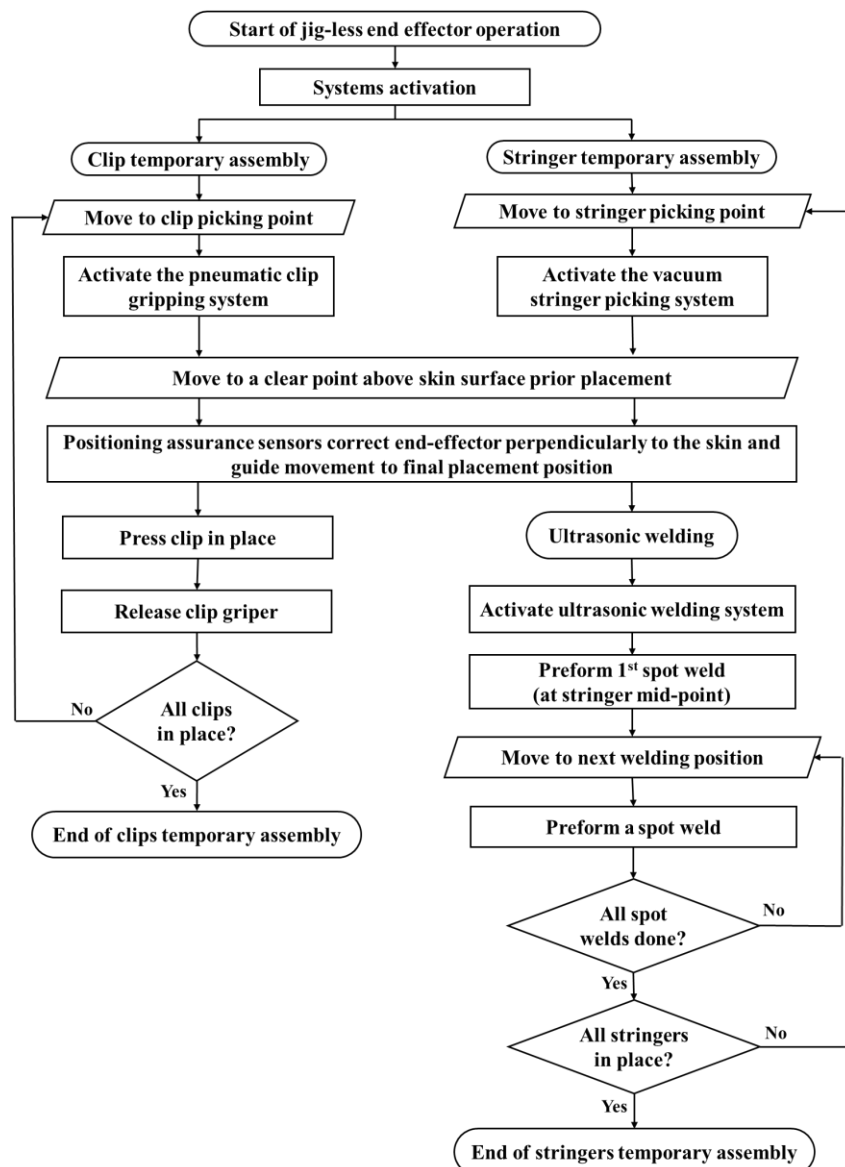


Figure 4. Process flow chart for clips and stringers assembly.

4. Stringers ultrasonic welding

As stated earlier, the development and design of the jig-less end-effector were reported in a previous study. In this section, the implementation and verification of the ultrasonic systems are presented in the following sub-sections:

4.1. Ultrasonic welding system components

The manufactured welding system comprises of an SPA20 Rinco ultrasonic welding actuator, acoustic stack formed by the converter, the booster and the sonotrode, and ADG 20 Rinco ultrasonic generator as seen in Figure 5 [7]. The ultrasonic welding tool is positioned at the centre of the jig-less assembly end-effector, with a slight lateral offset position that allows it to perform the spot weld following the placement of each stringer. As this completes, the end-effector transits to the corresponding weld spots to secure the stringer adequately as a temporary hold in place solution; final welding will be conducted using a long weld conduction tool [7].

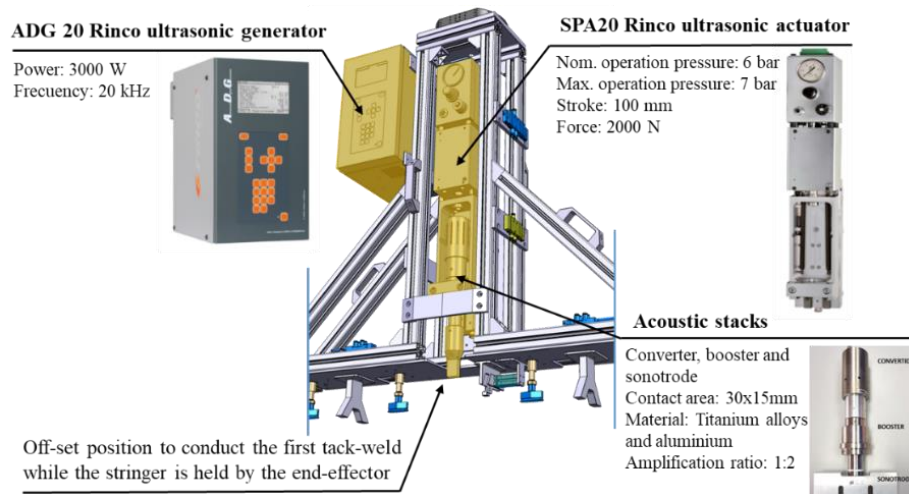


Figure 5. Ultrasonic welding system for stringers tack-welding operation [7].

4.2. Ultrasonic welding parameters

In order to conduct a successful ultrasonic weld, several parameters must be defined, these parameters are:

Welding method: For the welding method, energy is selected. The selection of this welding method means that the welding process will be controlled by the “Energy (W.s)” parameter defined by the operator. The equipment will use the energy defined as the maximum energy used in the process.

Trigger method: A trigger potentiometer is selected so that the welding process will start once the potentiometer reads that the force applied by the press (SPA20 actuator) reaches the trigger force defined previously by the operator.

Weld parameters: As the welding method and trigger method are defined, the next step is to set the welding parameters, including the energy value, pressure at which the trigger is activated, and the Amplitude.

4.3. Ultrasonic welding trials and verification

A series of weld trials were conducted and tested to define the suitable welding parameters that all guarantee achieving a successful weld that can hold the stringers in place. These trials included testing the ultimate tensile strength for four samples welded with three different energy parameters, 2,000 W.s, 3,000 W.s, and 4,000 W.s. All samples are prepared with the same carbon fibre reinforced thermoplastic composite, and welded at one spot, forming single lap shear tests specimens. Sandwiched between the two composite specimen sections are the energy directors. These are necessary because they focus the energy transmitted by the sonotrode to a specific place on the parts. The energy director is the part that melts during welding, resulting in a stronger joint between parts and a controlled weld (with focused energy). Apart from adding them to the welding stack, it is necessary to fix them to one of the two parts to be welded. In the case of this project, the energy directors were fixed using Kapton tape, preventing them from shifting during welding, and ensuring a strong and quality weld. It is also possible to use ultrasonic pre-weld to attach the EDs to the parts before the final weld is made. Figure 6 shows the tested samples and the test setup. On the other hand, Table 1 presents the ultimate tensile strength obtained for the tested samples.

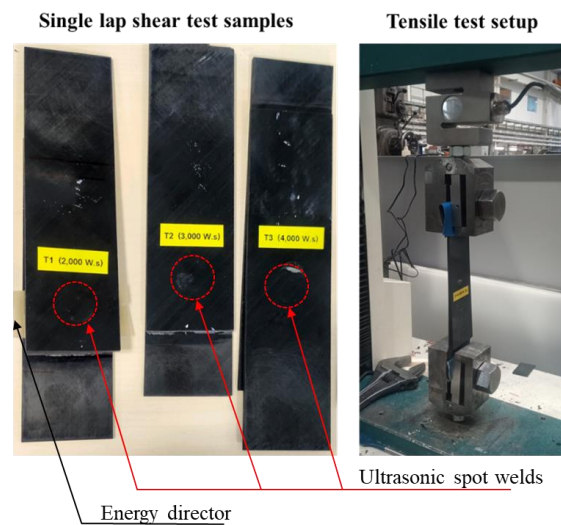


Figure 6. Tensile strength test samples and setup.

Table 1. Ultimate tensile strength results for the tested samples.

	Single lap shear test sample		
	T1	T2	T3
Specified ultrasonic weld energy	2000 W.s.	3000 W.s.	4000 W.s.
Ultimate tensile strength	2540 N	4035 N	2100 N

Tensile test for the samples in Figure 6 was conducted using a load cell of 50kN, at a displacement rate of 2mm/min. The results in Table 1 show that T2 sample, with a 3,000 W.s weld energy parameter, achieved the highest ultimate tensile strength. On the other hand, lower values for T3 (4,000 W.s) and T1 (2,000 W.s) were obtained, respectively. Nevertheless, all samples provided sufficient strength to hold the stringer in place using a single weld, until other spot welds are conducted; the strength needed to hold the stringer in place is 19.6N at the worst-case scenario, which is the longest stringer with 8 meters length (which weights approximately 1.99Kg), at the highest skin position, see the stringer marked with yellow in Figure 1. In terms of surface damage, no damage was seen T1 (2,000 W.s) sample, with minor damage in the case of T2 sample (3,000 W.s), and considerable laminate damage when using the energy of 4,000 W.s in T3.

Similar weld trials were conducted for stringer sections to assess the weld feasibility for curved skin sections rather than flat single lap shear tests samples, see Figure 7(a). Again, the process resulted in equivalent, high-quality welds, as seen in Figure 7(b).

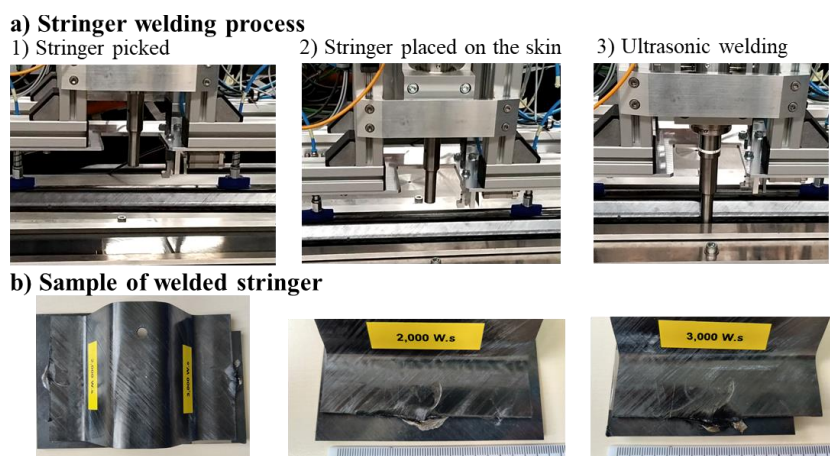


Figure 7. An demonstration of jig-less end-effector stringer-to-skin ultrasonic welding process.

4.4. Welds optical microscopy

Welded samples, namely with higher energy, showed surface deformation and heat damage. Therefore, optical microscopy was conducted for two different weld energies, 2,000 W.s and 3,000 W.s. Microscopy samples were prepared by sectioning the required spot welds, and then mounted in resin to ensure easy handling during the microscopy analysis, and avoid damaging and contaminating the material structure with debris while polishing, see Figure 8(a). Images were captured using the Leica DM6000 optical microscope.

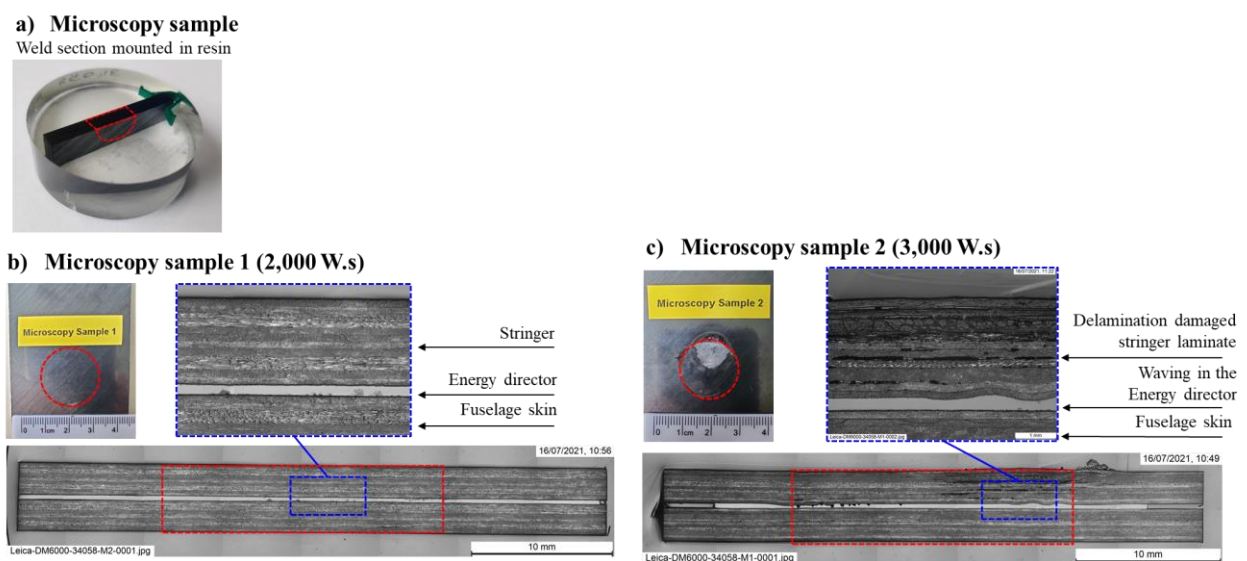


Figure 8. Optical microscopy for ultrasonically welded samples.

The optical microscopy images in Figure 8(b) for the 2,000 W.s energy welded sample show no evident damage to the composite laminate, and the energy director layer appears to be uniform. However, the 3,000 W.s microscopy sample show clear through-thickness damage to the stringer laminate in what appears to be delamination and matrix cracks. Additionally, the energy director experienced noticeable waving along the length of the welded region.

5. Conclusion

This study presents the application and verification of the jig-less end-effector system developed for the automation of exhausting composite fuselage assembly tasks. The developed end-effector systems is part of TCTool project that offers a comprehensive solution for assembling a full-scale multifunctional integrated composite thermoplastic lower fuselage section. The jig-less end-effector system is responsible for picking, placing, and temporarily fixing 38 stiffening thermoplastic omega-stringer, and 206 injection moulded thermoplastic clips. The solution development was driven by three main challenges: quality, scale and quantity of components, and process compatibility. In this study, the process flow for the assembly of these components is presented. Specific to the temporary fixing of the stringers, several trials were performed to assess the feasibility of the weld for tack welding the stringers until permanent weld takes place. It was concluded that ultrasonic welding with an energy of 3,000 W.s provides the highest ultimate tensile strength, yet some damage was observed in the laminate in contact with the weld (stringer's). On the other hand, samples welded with an energy of 2,000 W.s can provide sufficient strength to hold the weight of the stringer in the worst-case scenario by single spot weld; also, no noticeable damage to the composite laminate was observed in the microscopy. Whereas samples welded with an energy of 4,000 W.s resulted in considerable composite damage and lower strength. It is concluded that it is important to conduct trial welds when varying materials, thickness, back support, etc., to define the suitable weld parameters.

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