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Electromagnets for Aircraft Assembly

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Abstract – **Innovation in aircraft manufacturing and application and use of novel fabrication and assembly technologies and systems in aircraft factories is of crucial importance for Boeing. Maintaining high level of manufacturing equipment efficiency, and developing new production systems to improve quality and reduce cost, insures competitive advantage and establishes Boeing as the technology leader in aircraft industry. Major activities in building an aircraft involve assembly operations. Integration of detail parts to sub-assemblies, and building-up major components and the final aircraft, is accomplished utilizing a variety tooling, equipment and processes, ranging from manual tasks and large C-Frame riveting machines to robotic systems handling sophisticated Multi-Function End Effectors (MFEE). A common process step in all assembly operations involves clamping of parts (Stack-ups). This article provides information about electromagnetic clamping, an innovative methodology, enabling the creation and use of flexible automation systems for high level assembly tasks.**

Index Terms – **Mechanized, semi-automated, automated, AMP's (electric current), Multi-Function-End-Effector (MFEE), Manual Electromagnetic Burrless Drilling System (MEBDS), Gallons per Minute (GPM), Boeing Research and Technology (BR&T), Universal Splicing Machine (USM), Determinant Assembly (DA), Mitsubishi Heavy Industry (MHI), Horizontal Build Line (HBL), Massachusetts Institute of Technology (MIT), Electropermanent Magnet, Automated Wing Fastener Insertion System (AWFIS), Finite Element Analysis (FEA), Steel Backing Plate (SBP), Deployable Arm Robot (DAR), Process Control Document (PCD).**

I. Introduction

Today's aircraft assembly involves several methodologies and systems, ranging from conventional manual assembly to mechanized, semi-automated and fully automated systems. What assembly technology is being used, depends on type of components, structural configuration, available equipment, investment and level of innovation created during the development of advanced assembly techniques and systems. Conventional assembly processes are using manual tasks to join parts to small sub-assemblies, and integrating stepwise multiple sub-assemblies and panels to major components like fuselage and wing structures. Basic processes involved in manual assembly include: a) positioning detail parts relative to each other in assembly fixtures, or using determinate (pre-drilled holes generated during the part fabrication process) and tacking parts with Clecos; b) drilling/countersinking holes using hand tools (drill guns); c) disassembling parts, deburring hole exit areas and cleaning parts (removing chips and lubricants); d) applying sealant to faying surfaces; e) re-assembling parts and installing rivets or fasteners. The manual process is very time consuming. The figure 1 illustrates the behavior of parts during the manual assembly. As can be seen, the drilling is performed in-between two Clecos, and as soon as the first part is drilled, parts spring back, the drill bit continuous applying drilling force to the second part, resulting in a gap between parts, chips are entering the gap, necessitating part disassembly and cleaning, leading to a two-step assembly process.

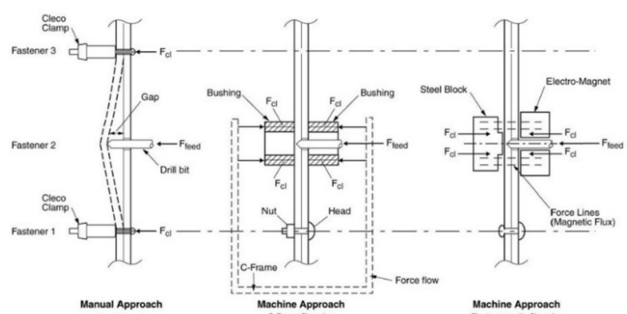

Figure 1 – Manual vs. Machine Process Principles During Drilling and Interference Fastener Insertion

Decades ago, aircraft manufacturers motivated machine suppliers to develop a machine, which could accomplish "One-up-assembly" by clamping pre-assembled parts at the drilling location to avoid gaps between parts, and to eliminate part disassembly and the cleaning process. A variety of C-frame and D-frame machines and systems are available today to perform “One-up-assembly” for rivets or fastener installation, significantly improving process efficiency and reducing time and cost of structural assembly. Machine part clamping requires two bushings (one on each side of the sub-assembly), and active and re-active clamping forces are carried around the part by the C-frame machine structure (see figure 1). Because of the force flow around the sub-assembly, only certain type and size of structures can be assembled with this machines e.g.: single, super and mega fuselage and wing panels, allowing access to both sides of the structure (open structure). Figure 2 and 3 show fuselage and wing type of structures and assembly levels required to build step by step a complete fuselage and wing. The fuselage is built in five assembly steps (single, super/mega panels, half shells, barrels and complete fuselage) and wing is built in four major assembly steps (single panels, spars and ribs, spar/rib grid, upper and lower panels assembly - creating the box), and integrating wing center box with the left and right wing box. However, if assembly of “closed structures” like fuselage barrels and wing boxes is required, these C-frame machines cannot be used. All assembly operations had to be performed manually.

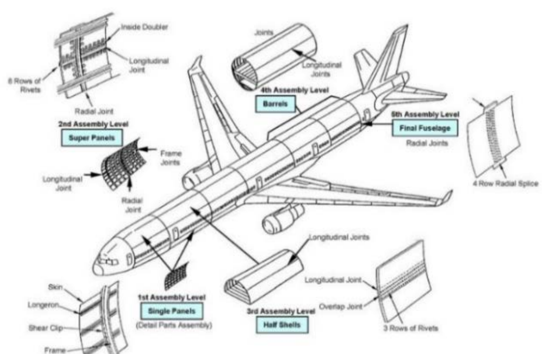

Figure 2 – Fuselage Assembly Levels and Joint Types

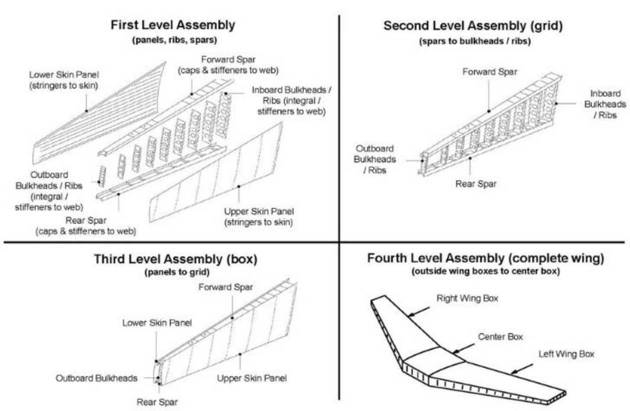

Figure 3 – Assembly Levels for Wing Primary Structures

II. MAGNETS FULFILLING NEED WHERE C/D-FRAME MACHINES CANNOT BE USED

Innovation and development of new assembly methodologies were required to eliminate manual assembly of “closed structures”. Leading the aircraft industry, we at Boeing invented (several patents were issued), developed and implemented semi-automated systems using electromagnets for “closed structures” such as fuselage barrel sections and wing box assemblies. Instead of C frames, to clamp sub-assemblies, we developed electromagnets, generating magnetic flux, penetrating the aluminum or composite structure, pulling a steel block (positioned inside structure) towards the electromagnet, and clamping parts in-between, as depicted in figure 1. Clamping force at the drilling location can be adjusted to satisfy process requirements by manipulating the voltage of the electromagnet and size of the steel block/plate inside the structure. Principles of clamping force generation with electromagnets and potential applications of these assembly methodology for fuselage and wing box structures are depicted in figure 4. For a given structural stack-up (gap) specific electromagnet process parameters must be used, (electric current, steel volume), to clamp parts sufficiently, eliminating gaps during the drilling/countersinking and interference fastener insertion. For thin structural stack-ups, low clamping forces will suffice (generated by applying low current to the electromagnet), however, for thick stack-ups, sometimes a magnitude higher clamping forces are required and are generated by applying higher current to the electromagnet.

One potential concept using electromagnets is with a flexible assembly systems, whereby the electromagnet is integrated with a Multi-Function-End-Effector (MFEE) moving on the rails positioned on the outside of the fuselage. A mechanic on the inside of the fuselage is handling a gun with a steel block, positioning it opposite of the MFEE to support the generation of clamping force. After a fastener is inserted by the MFEE, the mechanic will install a collar or nut onto the fastener with a hand tool. Similar methodology using flexible assembly systems can be applied to wing box structures. (See Fig 4)

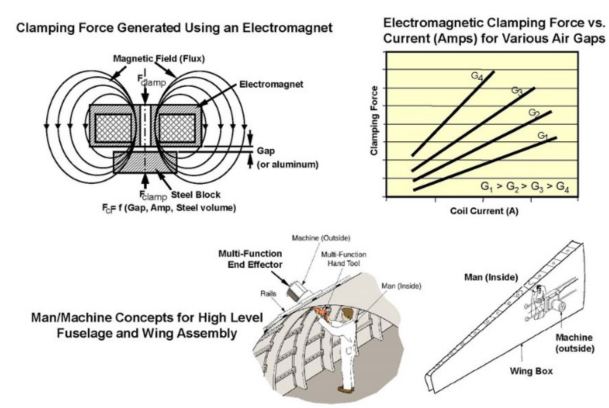

Figure 4 – Clamping Force Concepts & Aircraft Applications

III. ELECTROMAGNETS FOR MANUAL ASSEMBLY

The first application of electromagnetic clamping was developed for the C17 longitudinal fuselage joint assembly, performing manual one-up assembly. Figure 5 shows the Manual Electromagnetic Burrless Drilling System (MEBDS) attached to C17 fuselage panel. The system consists of a plate to which the electromagnet and the chip vacuum extraction unit is attached, and MEBDS is moving along the rail across the fuselage. Suction cups are stabilizing the rail on the fuselage surface. The mechanic is moving the plate with the electromagnet from hole to hole of the black template, attached to the longitudinal joint area. A steel block (see figure 5) is placed inside the fuselage onto the stringer to gain proper vertical position relative to the template on the outside of the fuselage, and an operator inside the fuselage is moving the steel block along the stringer. Prior to the panel placement onto the fuselage fixture, sealant is applied to both panels and panels are tacked with temporary fasteners. The electromagnet (hidden below the MEBDS plate) is activated prior to manual drilling/countersinking, and fastener feeding on the outside, and installing sleeve on the inside of the fuselage completes the “One-Up” manual assembly process.

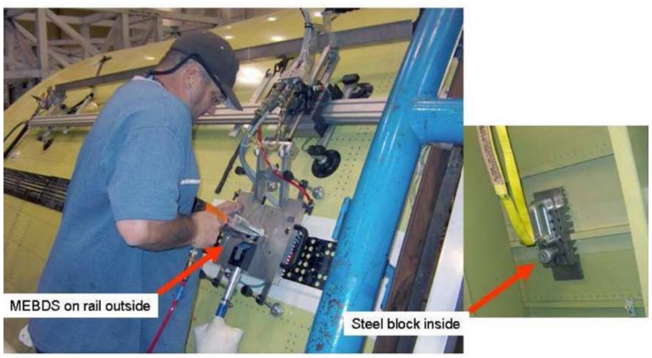

Figure 5 – Manual Electromagnetic Burrless Drilling System

Figures 5 & 6 illustrate the MEBDS system principles, showing the electromagnet activated, and the drill in countersink position with the drill tip exiting the part stack and entering the clearance cavity machined in the steel block. The steel block has multiple longitudinal grooves to accommodate processing multiple rows of fasteners and up to six fasteners along each groove. A magnet sensor communicates the position of the electromagnet to the mechanic.

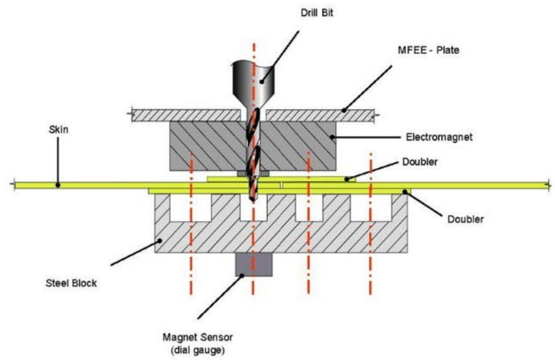

Figure 6 – Clamping Structures with Electromagnet and Steel Block During the Drilling Process

An electric coil inside the steel shell of the electromagnet generates heat, necessitating cooling to avoid damage to coil windings and wire installation. For low clamping forces, achieved by applying low current to the coil, heat energy generated can be removed by blowing pressurized air through channels in-between coil windings. This cooling technique was used for the MEBDS system. However, for maximum clamping force, water cooling is needed to sufficiently extract heat energy generated by higher electric current. Performance measurements and test results depicted in figures 7, 8, 9 show the relationship between current levels (amperes) and clamping force for a water cooled 8.5 inch diameter electromagnet. 0.5 inch thick steel plate, 10 inch square in size, served as standard geometry to perform force measurements, and was used for testing and comparing results for different end effectors. For structural stack-up of 0.2 inch (0.2 inch gap), 10 A yielded 180 lbs. clamping force, and increasing energy levels to 45 A, up to 1000 pounds of clamping force can be measured. Even for very large stack-ups of 1 inch, 45 A can still generate up to 200 lbs. load on the structure.

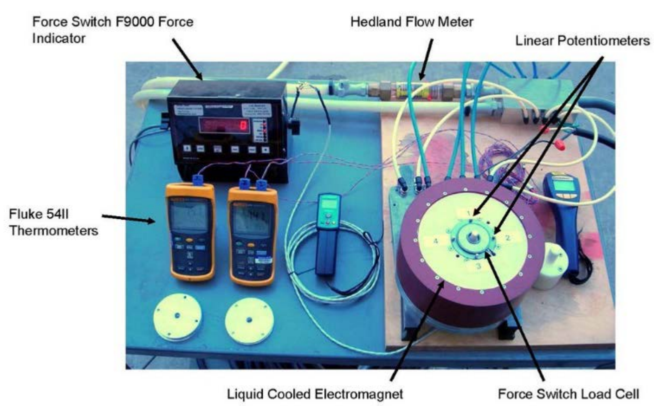

Figure 7 – Electromagnet Test Setup

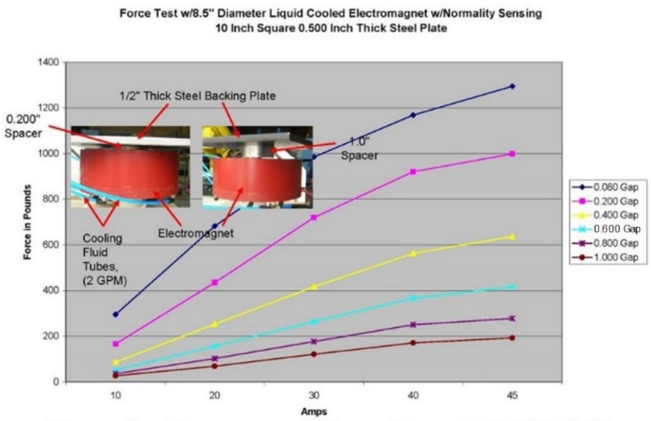

Figure 8 – Electromagnet Force Test w/10"x10"x0.5" Steel Backing Plate

The amount of heat energy extracted from water cooled electromagnets depends on the specific volume of water (gallons per minute GPM) circulated through cooling channels between the polymer-coated copper coil windings of the magnet. After activating the electromagnet, thermocouples indicate that temperature rises in one minute to approximately 100 degrees Fahrenheit, if only one GPM cooling fluid is sent to the electromagnet. Temperature will drop to approximately 95 degrees Fahrenheit if cooling fluid volume is raised to 4 GPM. Temperatures stay constant during the active electromagnet operation. It takes also one minute to cool the coil down to room temperature at the end of the cycle as shown in figure 9.

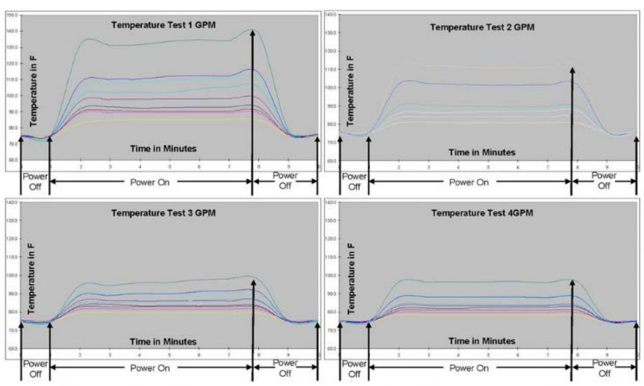

Figure 9 – Electromagnet Operating Temperature Test

IV. FLEXIBLE ASSEMBLY SYSTEM

Following the successful implementation of the electromagnetic clamping breakthrough technology into the MEBDS for C17 central fuselage assembly line, BR&T decided to develop a flexible semi-automated assembly system (based on electromagnetic clamping) for the C17 aft fuselage longitudinal joints. BR&T personnel developed the concept and Electroimpact was contracted to build a prototype. The prototype system "Universal Splicing Machine" (USM) shown in figure 10 was built and tested in the BR&T assembly lab in Long Beach. The following functions and capabilities were integrated into the prototype system: a frame carrying the MFEE moveable on rails in X direction, rails are stabilized on the fuselage with suction cups, MFEE (electromagnet, vision system camera, drill unit, fastener feed unit, and chips evacuation sub-system) is moving in Y direction inside the frame to access six rows of fasteners. All functions, motions and process steps are controlled by a computer.

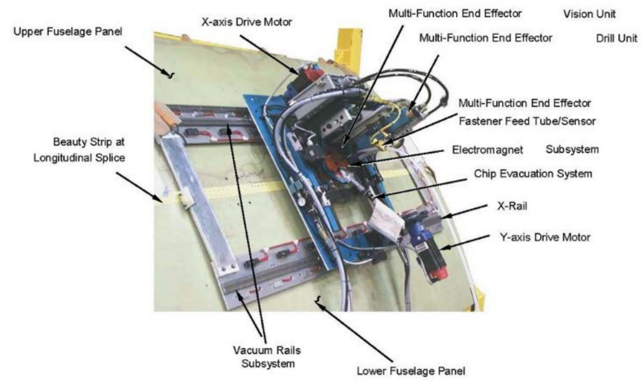

Figure 10 – Universal Splicing System.

Illustrations in figure 11 show the red electromagnet on top left with vision system camera inserted into the center hole of the electromagnet, two black air cooling hoses providing heat energy extraction, and in-between air hoses is the port for chip removal. On the upper right picture are steel backing plates, one positioned on top and one below the longeron, pushed against the longeron by two temporary clamps. The lower right picture depicts the lock-bolt tool inserted into steel plate hole, pulling the bolt and swaging the sleeve/collar onto the bolt as the pintail snaps at the designated pulling force. A miniaturized permanent magnet inserted into a pre drilled hole of the internal structure enables finding and marking the internal hole position on the outside skin, as shown in the lower left picture. The MFEE is positioned over the mark on the skin using the vision system prior to powering the electromagnetic clamp and initiating drilling.

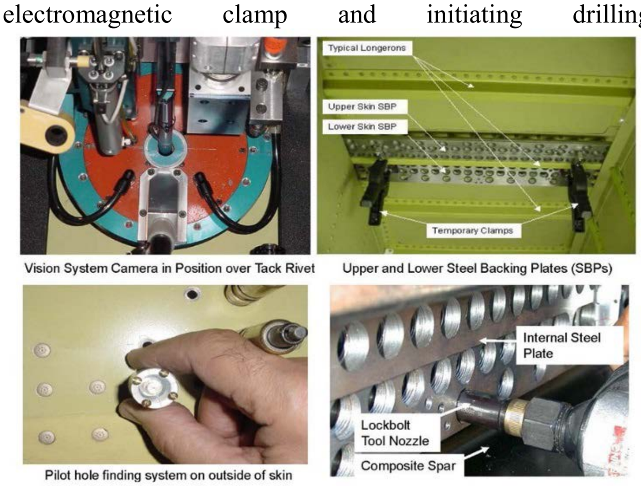

Figure 11 – USM Vision and Backing Plate Systems

Proper process parameters must be determined to ensure sufficient clamping force is generated for a particular electromagnetic design (diameter, number of coil windings, size of copper wire), backing plate thickness and structural stack-up. Clamping force measurements for the USM were performed on an Instron test machine depicted in figure 12, and results plotted in the graph provided data for selection of required current amperes, if a 0.5 inch steel plate is used. The graph is populated with test results ranging from 5 – 25 A which allows for picking needed parameters by extrapolating between curves of constant current. For stack-up of 0.43 inches, 9 A of current must be sent to the electromagnet to generate 105 pounds of clamping force. If the process requires 300 pounds of clamping force for 0.43 inch stack-up, the current to the electromagnet has to increase to 20 A.

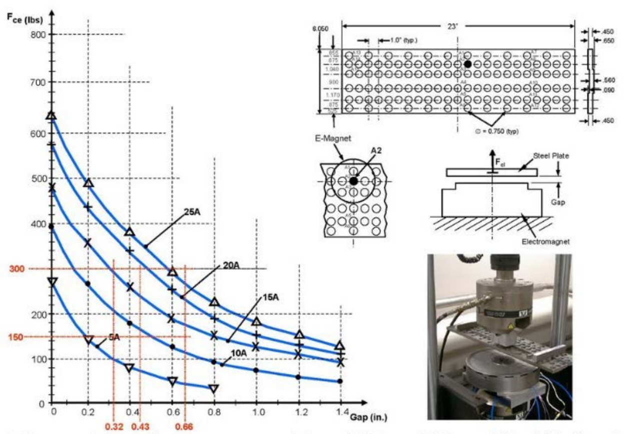

Figure 12 – Electromagnet Test (OD = 11”, t=3”), ½” Steel Plate (Position A2) Using Instron Machine (22,000 lb range)

The USM electromagnet is air cooled, and cooling channels are built into the eleven inch diameter steel shell surrounding the coil windings. Windings are separated by layers of cavities to allow 64 psi air flowing through the magnet to extract generated heat energy. The graph in figure 13 demonstrates a temperature rise of the electromagnet to a maximum 250 degrees Fahrenheit if held constantly under current of 25 A, utilizing air flow of 43 cfm.

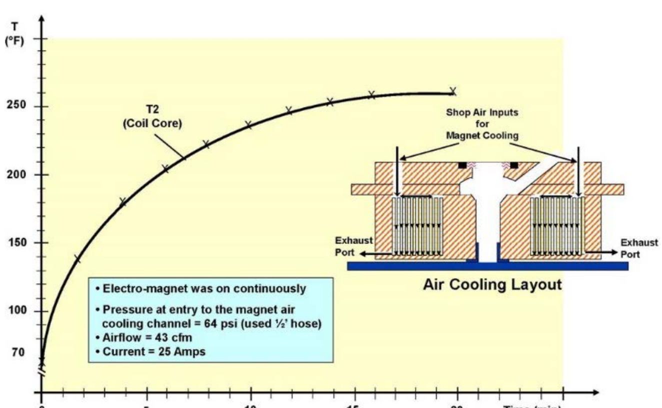

Figure 13 – Electromagnet Temperature Test

The C17 production USM performing fastener installation on aft fuselage (shown in figure 14), is an example of unwavering innovation towards establishing smart aircraft assembly factories in which automation, robotics, controllers, sensors and software are driving an advanced production system. The USM represents a departure from large expensive riveting machines and the move towards semi-automated, intelligent, flexible and affordable robotic type assembly systems, providing higher efficiency and improved quality. Comparing USM system in figure 14 with the manual MEBDS system in figure 5, it becomes obvious that the workload for mechanics/operator is significantly reduced, all process steps with USM are carried out automatically, and process parameters fed into computer program are driven by the systems controller, unlike with the MEBDS where all actions are performed by the mechanics (excluding electromagnetic clamping). Improved ergonomics and safety are additional benefits of the USM system. Computerized system enables data monitoring, collection and documentation, improving the quality control process and traceability of process parameters.

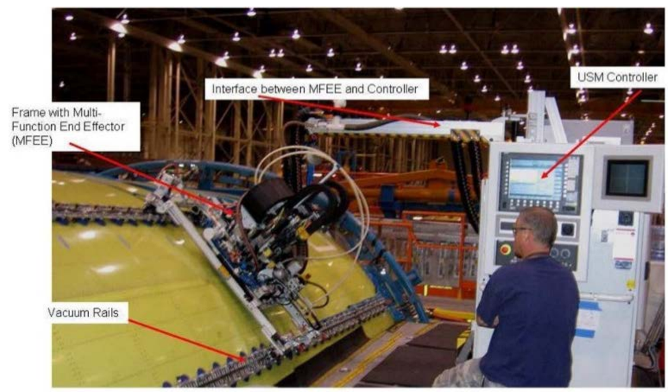

Figure 14 – Universal Splice Machine in Fuselage Assembly

Successful implementation of the Universal Splicing Machine for fastening closed fuselage structures marked a milestone whereby electromagnetic clamping technology had reached a production readiness level allowing replication. U.S. Patent 7,148,776, “Electromagnetic Clamp and Method for Clamping a Structure”, was awarded in 2006 and the technology could now be applied to thin stacks (< 0.5 inches) comprised of structures that can accommodate an 8.5” cylindrically-shaped magnet. However, additional technology development would be necessary to adapt the invention to thicker stacks and more diversely-shaped structures.

V. SYSTEM REPLICATIONS

With emergence of composite materials and innovative aircraft configurations, the assembly technologies had to be adapted to satisfy new process requirements. The 787 wing was the first composite commercial aviation primary structure embracing the advantages of these new materials. Furthermore, the traditional wing box major assembly methodology at that time was changing from a vertical to horizontal approach for the 787, thereby eliminating large expensive assembly jigs, and replacing them with Determinant Assembly (DA) philosophy. Pre-drilled DA holes during the part fabrication, enable pre-assembling and tacking components to create the wing box with minimized tooling. The horizontal assembly technique was also well suited to facilitate one-up assembly processes providing new opportunities for automation, BR&T was tasked with modifying and demonstrating the applicability of the USM system to the 787 horizontal wing assembly (Fig. 15).

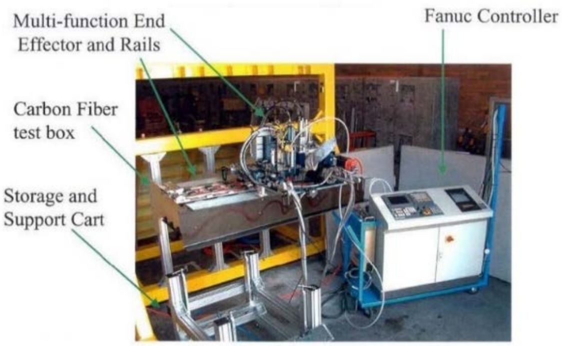

Figure 15 – Universal Splice Machine Process Sequence for 3/16" Interference Fit Fasteners

[Figures 16-18 and parts of Section V, and Section VI have been removed from the original proprietary paper.]

VII. FUTURE TRENDS

Today's competitive aerospace business demands that new automation increase rate, improve quality, reduce cost and improve safety. AWFIS fulfills the first two initiatives but comes at a high cost and with safety concessions. If electromagnetic clamping is going to prosper in the future, significant strides will need to be made to overcome these detractors.

For example, elimination of expansive recirculating water chiller systems will require new magnet technologies. The amount of energy required to generate 1,000 pounds clamping force for some 737 wing box lower panel assembly, generates a lot of heat. An elaborated fluid cooling system was built and implemented to keep HBL electromagnets below the 50 degrees Fahrenheit at all times, driving higher capital investments for production implementation.

Boeing is supporting the research at MIT with focus on new innovative concepts to reduce or eliminate the need for electromagnet cooling. Potential solutions investigated and tested at MIT involve the combination of permanent and electromagnets called electropermanent magnet assembly (see test unit in figure 35). An AL NI Co permanent magnet is surrounded by a copper coil and those are placed inside a steel shell. On the opposite side of the simulated aluminum stack-up is a steel plate which is pulled towards electropermanent magnet after magnet activation. The function of the copper coil is to magnetize and/or de-magnetize the AL NI Co permanent magnet. Magnetic flux density and corresponding clamping force between electropermanent magnet and steel plate is controlled by the magnitude, direction and sequence current pulses through magnetizing coil. To nullify the established magnetic field of the permanent magnet and correspondingly minimizing or eliminating clamping force, an electric pulse is applied through the coil in a reverse direction from the one used for magnetizing. With the modulation of the input current magnitude and direction, and to the sequence of momentary pulses (on the order of milliseconds) the AL NI Co core material is partially magnetized or de-magnetized. Once the target clamping force is achieved, no input energy is required to indefinitely maintain the clamping force. Because of very short energy pulses needed to magnetize or de-magnetize the system, no heat is generated eliminating the need for any electropermanent magnet cooling system.

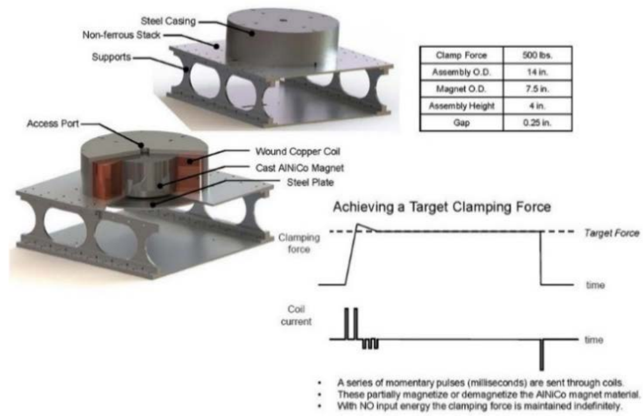

Figure 35 –Electropermanent Magnet Concept -Test Set-Up.

Another future trend will surely be the development of confined-space automation for handling steel backing plates to eliminate the ergonomic and safety issues associated with the current process as well as non-value-added extra work. A prototype Deployable Arm Robot (DAR) that could enter wing box to position steel backing plates for AWFIS was tested but did not prove robust enough for production (Figure 36). However, technological advances in the future should open doors for this type of automation.

Figure 36 –Prototype Deployable Arm Robot (DAR) positioning steel backing plate inside wing box.

To handle steel backing plates when fastening upper panels (prior to loading lower panel), robots will easily be able to be utilized as long as facilities are designed to accommodate. Robots will overcome the gravity challenge (holding the steel plate up during fastening), however clever steel backing plate designs will need to be developed to limit the number of steel plate geometries required. Nevertheless, the automation will require a multitude of plates with quick-disconnect adapters and stored in a tool changer.

Worth mentioning is the possibility of utilizing alternative magnetic clamping devices, such as trapped-flux superconductors which have already been successfully incorporated into flexible "pogo" tooling fixtures used to hold mandrels while laying-up, curing and trimming composite panels. (See Michael Strasik, "Trapped Flux Devices for Manufacturing", Chap. E2.4 in Handbook of Superconducting Materials). In the future, this or other alternative methods of generating magnetic fields could be adapted to automated fastening systems to alleviate the need for cooling.

VIII. SUMMARY/CONCLUSIONS

Developing and integrating electromagnets into aircraft assembly systems was a major innovative step in improving assembly processes for manual and semi-automated operations. The design and equipment characteristics were described in some detail, and opportunities for advancing the part clamping methodology with emerging electropermanent magnets was demonstrated. University research and in-house assembly system development activities should focus on this electropermanent technique to establish knowledge base for future system improvements.

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