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True Offset Fastening

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ABSTRACT

An automated machine has been designed with true offset fastening to join shear-tie/ frame assemblies to the fuselage of the Boeing 787 Dreamliner. The machine can access fasteners located close to structural components that are very deep. This is accomplished by offsetting the fastening axis from the axis of the head for true offset fastening. The head can be positioned next to the structural component and the offset fastening tooling 'reaches' out to the fastener location (Figure 1).

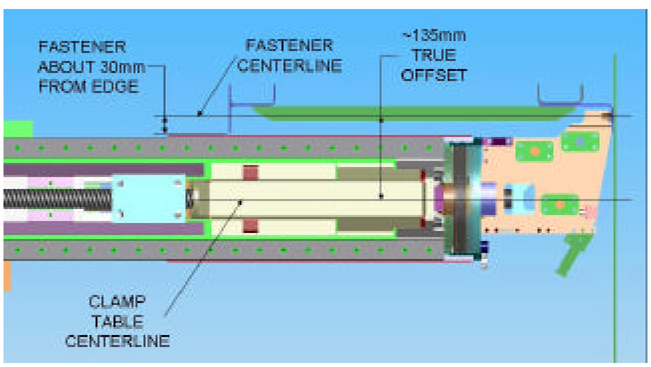

Figure 1: True Offset Fastening

By using a true offset, the fastening machine can access fasteners that would be otherwise inaccessible by traditional automated equipment. The machine can also be lighter and more accurate when compared to fastening machines with traditional tooling.

INTRODUCTION

Unlike conventional aluminum aircraft, fuselage sections of the all carbon fiber Boeing 787 Dreamliner are built as one-piece-barrel (OPB) sections (Figure 2). The OPB design complicates access for automatic fastening machines by requiring two independent machines, one inside and one outside the OPB. Fastening is further complicated by the presence of the cargo floor beams in place at the time the shear-tie/frame assemblies are fastened to the OPB. Since the distance between the cargo floor beams and the fuselage skin is very deep, it is difficult to access the fasteners between the shear-tie/frame assemblies and the inner surface of the fuselage skin. Nevertheless, since 20% of the shear-tie/frame assembly fasteners occur in the area under the cargo floor beam, the search for an automated fastening process is justified.

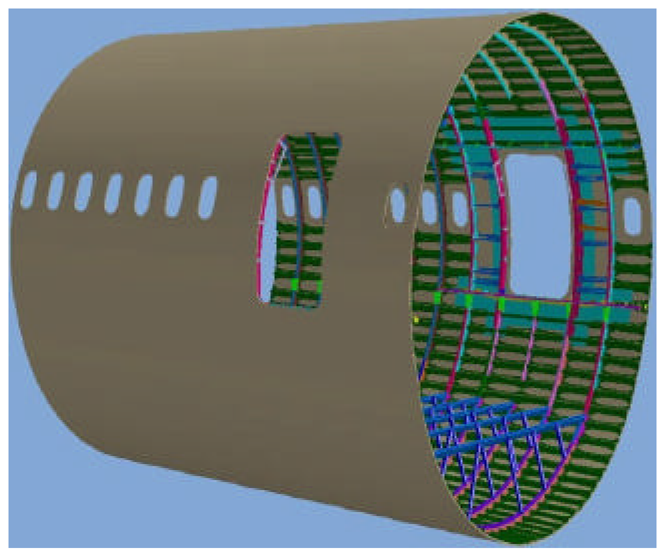

Figure 2: Boeing 787 One Piece Barrel (OPB) Design

The difficulty in designing an automated fastening machine is how to access these fasteners while maintaining alignment between the heads at the fastening point that is required for accurate and repeatable installations.

Traditionally, the centerline of the fastening process (center of the fastener driving force) is located at the centerline of the head (Figure 3).

In order to access fasteners hidden by or close to the cargo floor beams in the case of the 787 fuselage, the traditional in-line tooling would have to reach over 750mm (Figure 4). The machine weight would have to increase to maintain the stiffness because support bearings and machine structure is pushed farther from the fastening point with the longer tooling. Also, the run-out or alignment errors of such long tooling would add to the misalignment errors between the heads and would be difficult to maintain in production.

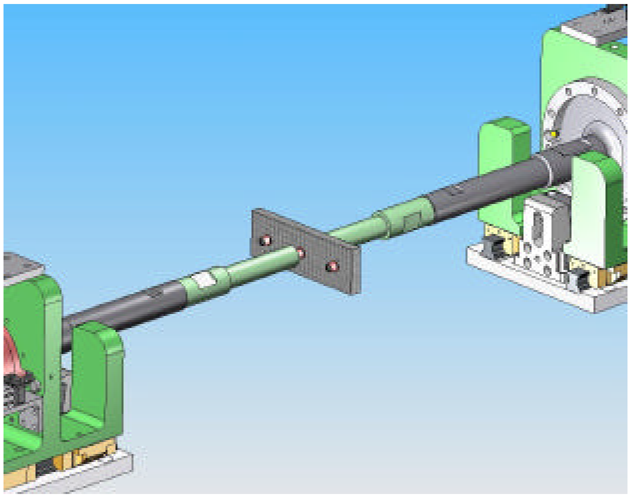

Figure 3: In-line on axis fastening.

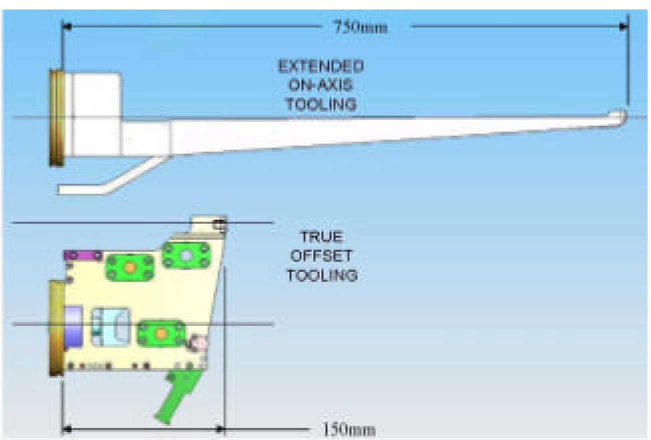

Figure 4: Traditional tooling vs. True Offset Tooling

Therefore, deep drop fasteners are typically installed manually.

At Electroimpact, we designed an EMR fastening head with a true offset tool where the fastener centerline can be offset from the head centerline by 135mm (Figure 1). Also, because the EMR is a low inertia system, the machine does not have to react the large loads created during the fastening process. Thus the EMR gives greater flexibility in machine design because the supporting machine structure can be smaller and lighter. The narrow EMR head can fit between the cargo floor beams to access fasteners on either side of the frame bay while supporting tooling that is only 150mm long (Figure 5). The machine gains access to many previously inaccessible fasteners while maintaining the accuracy and reliability achieved with traditional automated machines.

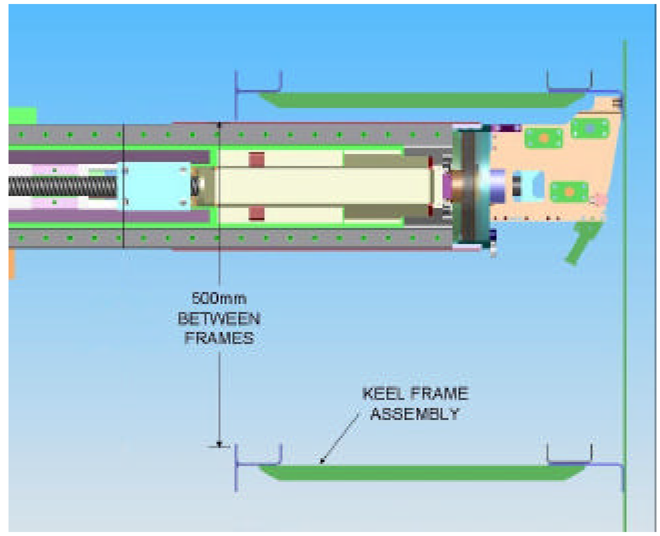

Figure 5: Access to fasteners

This paper describes our approach to the problem, and describes the final design of the production equipment.

PROBLEM DESCRIPTION

Fastening the shear-tie/frame assemblies inside of the one-piece-barrel fuselage design requires two independent machines – one located inside and one located outside of the fuselage (Figure 6). Maintaining accurate head alignment between the independent machines over the large working envelope is required as it dictates the reliability and quality of the fastener installation.

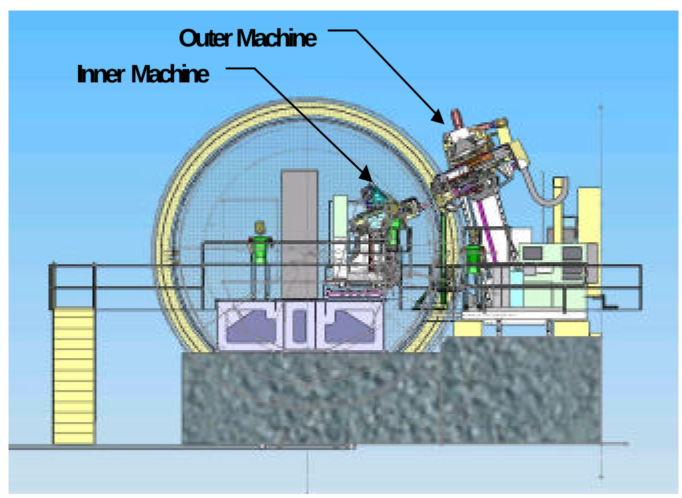

Figure 6: Independent Machines

The inner machine must fasten shear-tie/frame assemblies to the inner skin surface or inner mold line (IML) of the fuselage. Since the fastener is close to the shear-tie/frame assemblies, the machine head must clear the cargo floor beams in the keel of the aircraft. Cargo floor beams create a deep inboard-outboard drop from the top of the beam to the IML surface. This requires long fastening tools that have to reach at least 750mm into the fuselage.

The tooling must also rotate about the centerline of the head or the C-axis since the tooling must be oriented in either the forward or aft direction (Figure 7). If long tooling is used, the C-axis rotation bearings are pushed further from the fastening point. Consequently, any run-out caused by angular error of the tooling is amplified when compared to run-out of shallow drop tooling. The run-out directly adds to the misalignment errors between the inner and outer machine heads.

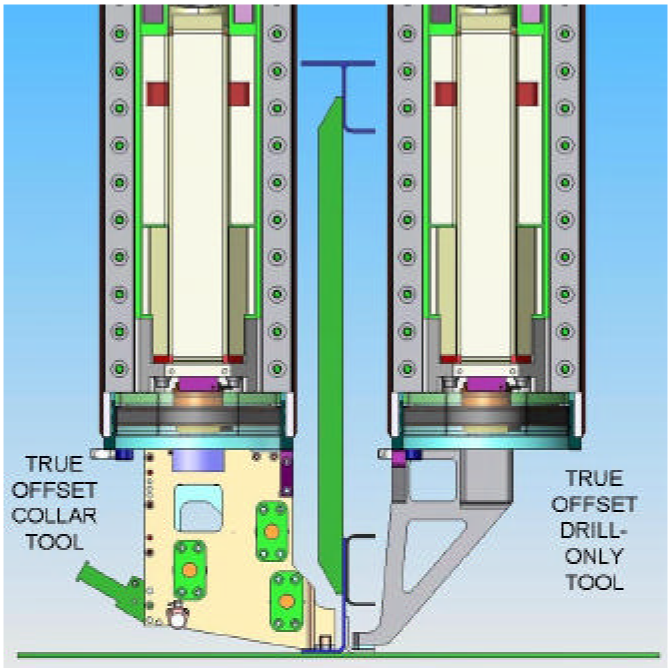

Figure 7: FWD/AFT access required

The pitch of the shear-tie/frame assemblies leaves only about 500mm of clearance between the cargo floor beams (Figure 5). The head width is further limited to provide clearance for maneuvering between the shear-tie/frame assemblies and also access both forward and aft fasteners.

Rigidity of the machine also effects head alignment. Since the OPB is a closed cross-section (only open at the ends), rigidity of the machine is reduced because the inner machine cannot be supported by a typical foundation along the entire X-axis travel.

Swaging 5/16 CT collars requires an output force of approximately 3,200kgs and clamping forces are over 500kgs. Long tooling reduces the rigidity of the machine by moving the supporting machine structure further from the fastening point. The designer must increase the machine weight in order to maintain the stiffness required for reliable installations.

SOLUTION: TRUE OFFSET FASTENING

Electroimpact has designed a fastening head for the inner machine where the fastener centerline is offset from the head centerline. The advantage is being able to drive the machine head close to fasteners that adjacent to any tall structure while still using a relatively short tooling length compared to traditional in-line tooling.

The offset required for the 787 fuselage shear-tie/frame assemblies is 135mm from the center of the head. The head itself is only 200mm wide. The offset is sufficient for the tooling to reach the fastening point of the shear-tie/frame assembly while maintaining clearance between the head and the cargo floor beams. The narrower head allows access between the cargo floor beams to fasteners forward and aft of each frame bay.

The tooling drop is minimized at 150mm keeping the C-axis bearing only 270mm from the fastening point, similar to more traditional tooling and high performance machines. This also decreases the distance from the main machine positioning axes to the fastening point and consequently, the machine design is more compact to maintain stiffness and reduce weight (Figure 8).

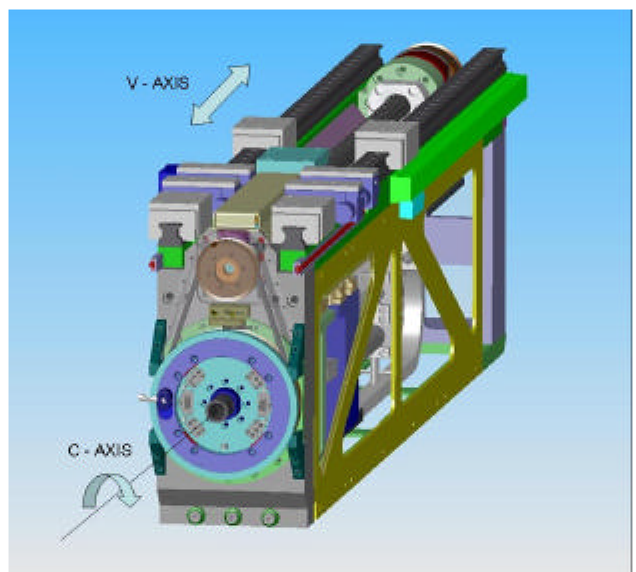

Figure 8: Inner Machine True Offset Head

The weight reduction becomes an important issue when working on the OPB because the inner machine cannot be supported along the X-axis travel. Instead, the inner machine rides on a steel structure which stabs through the OPB and is only supported at each end (Figure 9).

Lacking a proper foundation, the inner machine weight must be minimized to reduce the deflection of the supporting steel structure as the machine travels in the forward-aft axis of the fuselage. In turn, this reduces the misalignment between the inner and outer machine heads as the machines move throughout their travel length.

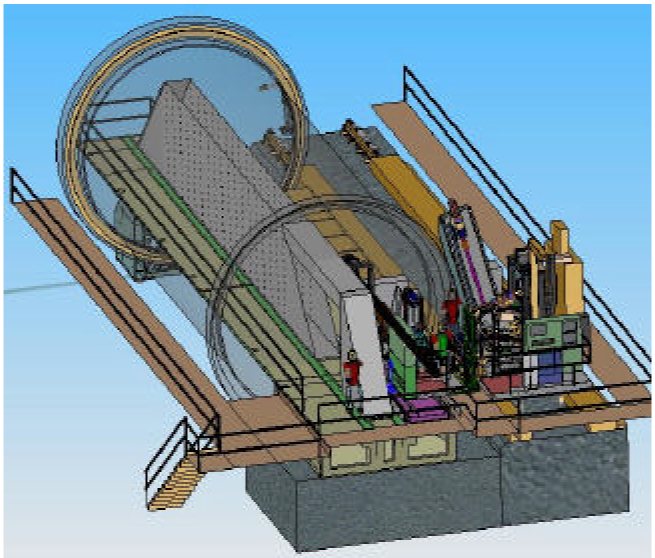

Figure 9: Cell Layout

The EMR allows us to react the forming forces in the head as opposed to the structure of the major machine. Theoretically, on the traditional in-line fastening machine, there are no moment loads created during to the fastening process. When the EMR guns are fired, the fastener forming force is absorbed along the axis of the fastener by the fastener itself and the recoil system in the EMR (Figure 10).

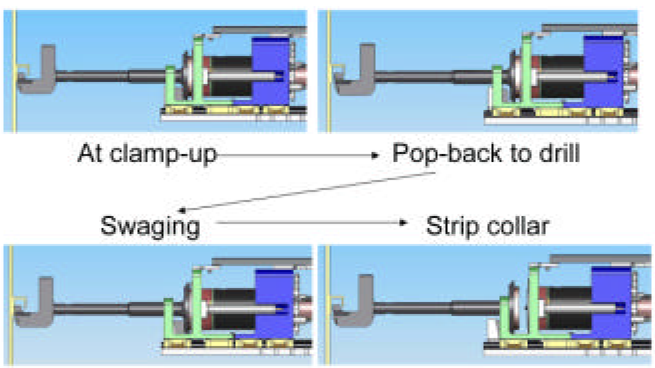

Figure 10: EMR operation

In the true offset machine, however, moment loads are created during the fastening process due to the offset centerlines (Figure 11). Since the geometry of the shear-tie/frame assemblies and the width of the head determine the offset distance, head width is minimized to reduce moment loads. The main innovation is resolving the moment loads of the fastening process within the tooling itself in order to transmit the forming forces efficiently and to protect the tooling.

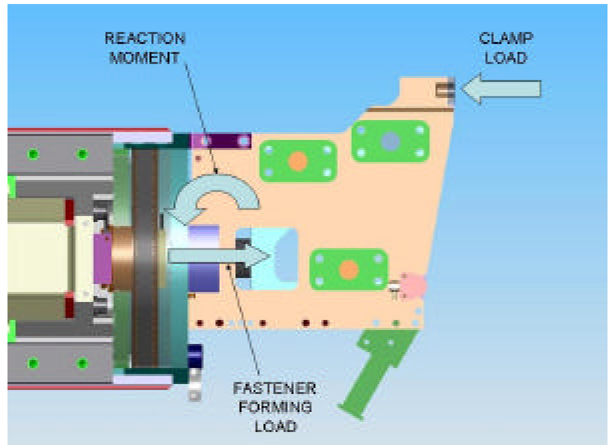

Figure 11: Offset Fastening Loads

PERFORMANCE METRICS

The true offset tooling must perform as well as traditional in-line tooling during swaging to producing high-quality fastener installations. Every inch of offset from the tool centerline adds over 790Nm to the resulting moment load. The means used to control this moment cannot add appreciable drag or the forming forces will be reduced. So the tool deflections must be controlled for both accuracy and efficiency.

The EMR process pushes a driver through an axial driver bearing toward the part. A ram and die attached to the end of the driver form the fastener (Figure 12). The ram and die operate within a set of clamp forks attached to the C-axis on the front of the clamp table. The driver bearing is located at the center of the c-axis and is supported by a stiff cross roller bearing designed to take the moment loads imparted by the offset clamping and forming of the fastener.

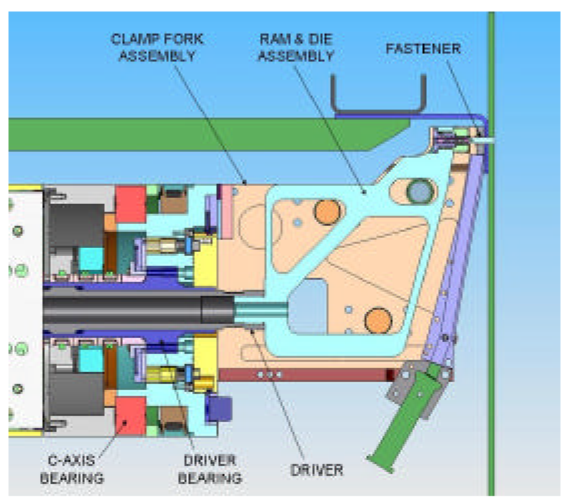

Figure 12: Tooling Layout

The clamp forks serve double duty clamping the parts together against the outer machine as well as transporting the collar to the tool point for installation on the tail of the bolt prior to swaging. The clamp forks add to the moment load seen by the v-clamp table. Clamp pads are ultimately placed just around the fastener and therefore share the same moment arm. The clamp load is less than the collar forming force, but at 250 – 500kgs, it is still significant.

The first step in controlling these moment forces was to create a linear support as far away from the tool centerline as possible. This was achieved by adding a pair of posts on the edge of the clamp table just outside the c-axis (Figure 13). The clamp forks are able to rotate over the posts with zero clearance and then once clamped up, the clamp force is resolved through these posts into the clamp table rather than by a rotational force at the quick-connect in the center of the C-axis.

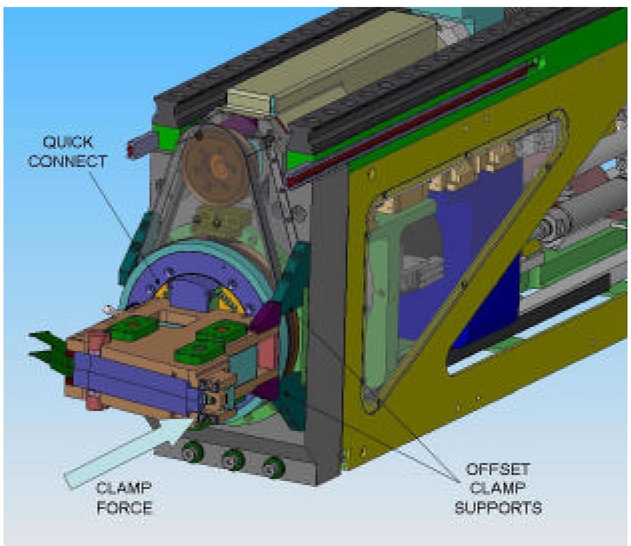

Figure 13: Clamping Loads

Now that the clamp forks are rigidly supported between the fuselage and the machine, they can be used to control the forces being imparted into the ram. Unchecked, the large moment force previously mentioned would produce the following unwanted effects.

First, the connection point between the ram and the driver would be under large stress loads and would fail after only a small number of cycles.

Second, the driver would see large bending forces and deflect inside the driver bearing. This would quickly wear the driver bearing and would also produce a lot of drag, making the forming process inefficient. The inefficiencies would require higher EMR voltage to push the driver forward. This would increase the load on the tool, which would increase the bending and drag, which would increase the inefficiencies, which would require higher EMR voltage, etc, etc.

Lastly, the ram itself, uncontrolled, would see very large deflections both parallel and perpendicular to the fastener centerline as the ram rotates up and away from the driver bearing. The parallel deflections show up as inefficiencies as the elastic deformation would result in an unperformed collar that would require higher EMR voltages to compensate and again, start that circle of cause and effect. The perpendicular deflections would “smear” a rivet head or in the case of collar forming, result in a side load on the bolt and an angular forming line on the swaged collar, neither one is acceptable.

To control the ram deflections and resolve the moment loads while still maintaining the required tooling profile, an array of bearing supported shafts were designed into the tool (Figure 14). The clamp forks have three pairs of roller bearings mounted to the side plates. These roller bearings support three shafts that run between the plates, through the ram. The ram in turn has three cut outs that allow the shafts to pass through, but more importantly, provide bearing surfaces to react the ram load into the shafts, and then into the clamp forks, and ultimately into the clamp table, rather than through the driver bearing (Figure 15).

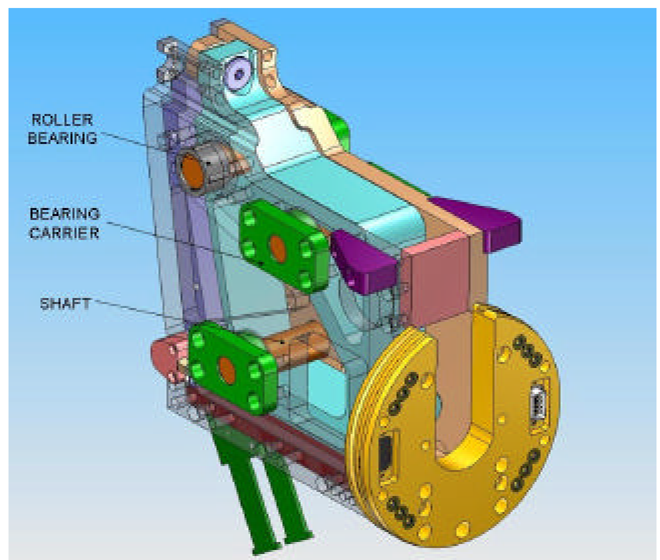

Figure 14: Offset Fastening Support Bearings

Each bearing and shaft arrangement shares a portion of the moment load that arises during collar swaging. The two forward sets directly counter the rotational forces in the ram while the rear set counters the ram’s internal reactional deflection to eliminate side loads on the driver bearing. The use of these rolling supports induces very little friction into the system. And combined with the elimination of the majority of the ram deflection, the system is very efficient.

All of this combines to produce a tool that is able to access previously unreachable fasteners and swage collars at the same high efficiency of the rest of our on-axis tools. The stresses in the components are also all well within the acceptable range and the fastened joints pass all aspects of the joint and fastener installation inspection with no problems.

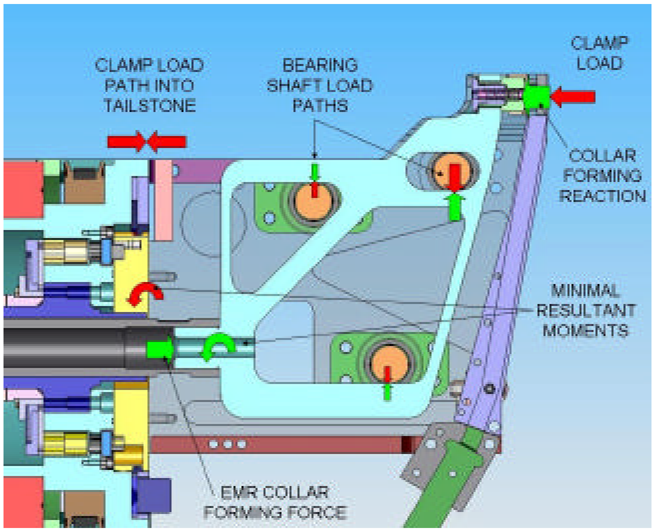

Figure 15: Load Path

The tooling was compared to a traditional in-line tooling assembly on a test bench. The power needed to form the same size fasteners in the same material was within 2.5%.

INNER MACHINE HEAD (CLAMP TABLE)

Because of the low inertia of the EMR system, the structure of the head can be small and lightweight (Figure 16). Also, the width of the clamp table must be minimized in order navigate the fuselage structure. Minimizing the clamp table width also reduce reduces the fastening offset required which, in turn, reduces the moment loads seen by the machine while forming the fasteners.

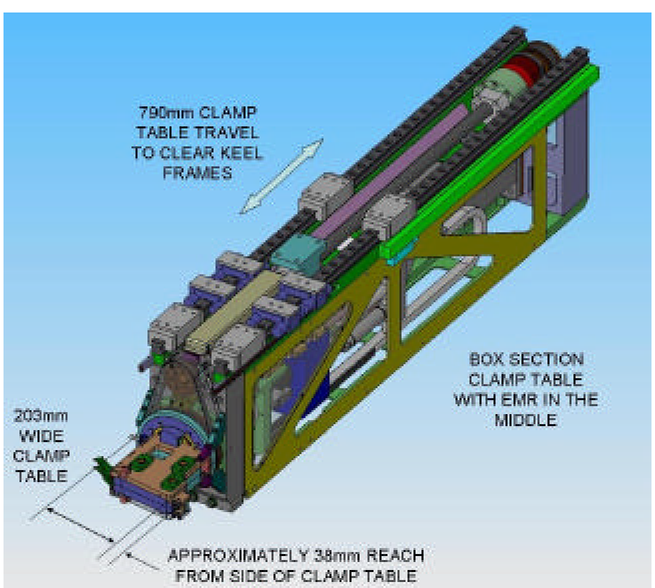

Figure 16: Inner Machine Head

The inside machine head contains a ball-screw driven clamp table (V-axis), a belt driven C-axis used to rotate the inner tools (0 +/- 180 degrees of rotation), and an EMR. On our previous LVER fastening machines, this combination was 305mm wide at a minimum.

To narrow the components down to a 200mm wide package while maintaining the performance and accuracy of the previous inner heads, the clamp table was changed to a box section with the main upper beam machined out of a solid steel billet. This produced a very stiff clamping axis to mount the rotational C-axis to. The EMR is now mounted inside the box section rather than under-hung as on the LVER machines. This has an added benefit of keeping the EMR centerline very close to the center of the inner machine.

TOOLING WEIGHT

The tooling weight is important for two reasons. First is process related. Since the EMR process is largely momentum based, the weight of the driver/ram/die combination relate directly to the required voltage to form a fastener. Since this project uses traditional on-axis rams which are much smaller than the offset ram, it was important to design the offset ram to be as light as possible to minimize the difference between the tools and simplify the certification process. A light ram also minimizes the inertial loads imparted into to clamp fork supports. After a number of iterations, checking results with ANSYS along the way, a final design was approved which matched the weight of all the ram/die combinations within 1% of each other, at about 2.5kgs each.

The second consideration is operator handling/ergonomics. A machine operator must be able to comfortably carry out a tool change without the intervention of cranes or other lifting/supporting equipment. The tool therefore must weigh no more than 11.3 kgs. As this tool is larger than our traditional tooling (due to the reach) as since the ram and clamp forks are an integral assembly rather than two separate units, that limit was a tall order. However, because we were able to produce such a light ram, and since we are using the gripper-less collar feed system which reduces the part count and complexity of the clamp forks, we are able to deliver a tool weighing just 9.6kgs.

TOOLING LIFE

A reasonable tool life is important to achieve due to cost, schedule, and process integrity. The only perishable items in the assembly are the dies, die springs, and die caps. Swage dies do wear over time and must be replaced. We used the same tool steel used with great success on the rivet and collar swaging dies used on previous Electroimpact machines. Using a swage cavity design recommended by HUCK, these dies are capable of swaging 100,000 collars without failure. When cleaned properly of any sealant/swarf build up, the die springs have a similar life. The die cap is much more susceptible to damage and mistreatment but is made from cast polyurethane and is therefore very inexpensive.

Because all of these parts last a minimum of a tool change, the operator is able to perform a quick visual inspection and upon successfully completing a set-up coupon, continue running the program without interruption. This helps eliminate schedule impact due to constantly changing broken/worn perishable parts.

Process integrity is upheld as well since the parts wear very slowly. We are able to record the relationship between the die and collar before each swage so if this relationship falls out of range over time, the operator is notified and a new die is quickly installed. If any of the parts in this process fail, this type of check will flag the operator of a problem and not let the machine proceed with a fastener installation. This protects the aircraft parts from damage resulting from worn machine parts or even catastrophic failures.

INNER MACHINE WEIGHT

The suspended structure that supports the inner machine throughout the X-axis travel must span 16m to accommodate section 43 (Figure 17). The structure, or inner floor, is bolted to a concrete pedestal on the foundation at one end of the cell. The inner floor is cantilevered from the pedestal to provide clearance for the fuselage when it is moved into the cell (Figure 18). Once the fuselage is positioned in the cell, a support is placed at the other end of the inner floor. The pedestal and floor support provide a fixed and simple support to react the dynamic load created as the machine moves along the floor.

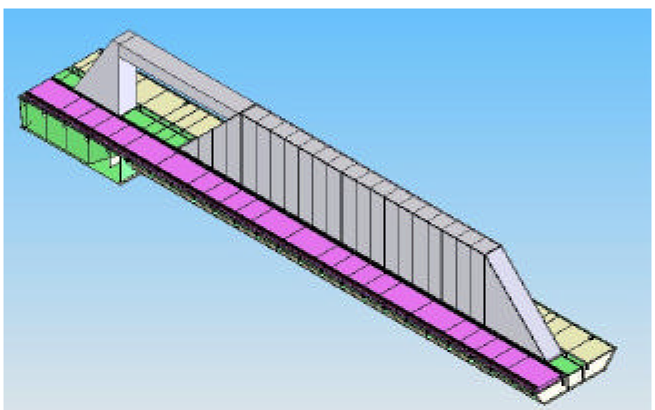

Figure 17: Inner Machine Floor Structure

The inner floor deflects as the inner machine moves along the X-axis and this causes roll-pitch-yaw positioning errors at the machine tool point. Most of the positioning errors can be compensated in the CNC control, however, the magnitude of the uncertainty error is proportional to the magnitude of the original deflection errors. If the magnitude of the inner floor deflection is minimized and so is the uncertainty error. Therefore, reducing the machine weight directly decreases positioning errors.

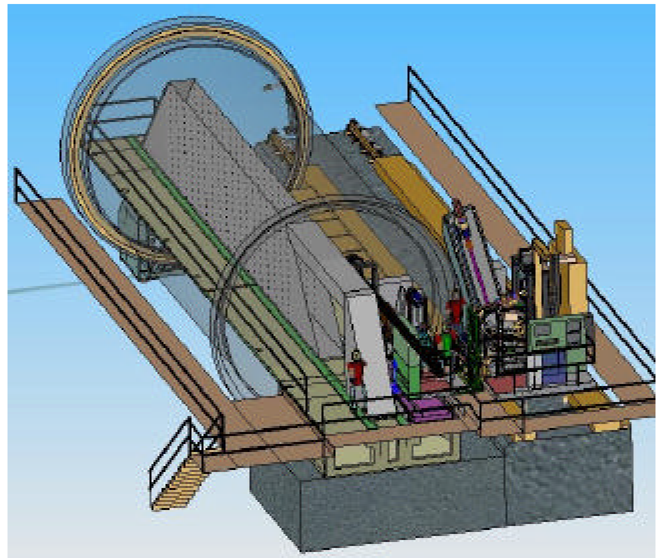

Figure 18: Cell View

By using true offset tooling, the machine weight is minimized because all of the machine components are moved closer to the fastening point.

The cargo beam floors require the stroke of the clamp table to be at least 750mm. Since the clamp table bearing rails are mounted on top of the clamp table, the machine structure that supports the bearing cars can be mounted relatively close to the fastening point as well. This keeps hardware for all of the machine axes - X, Y, A and B – close to the fastening point.

The resulting inner machine weight is 10,430kgs. Our target for vertical (Y-axis) deflection was keeping the overall deflections below 0.500mm for the inner floor. More than that adds complexities to the compensation algorithms that increase the errors of uncertainty. As determined by finite element analysis (FEA), the maximum Y-axis deflection of the final inner floor design was 0.338mm at 12m from the fixed support end (Figure 19). The actual measurements were 0.330mm.

The result of all the composite errors between the two machines throughout the working envelope is +/- 0.150mm.

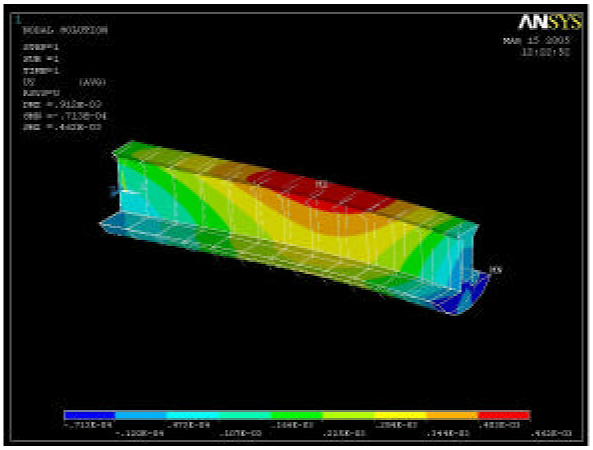

Figure 19: Inner Floor FEA results (Y-axis)

CONCLUSION

The True Offset Fastening head meets all of the requirements for fastener installation on the 787 Dreamliner Fuselage Section 43. The offset tooling improves access to many areas previously inaccessible to automated equipment while maintaining production hardy alignment and reliability. The EMR system gives flexibility to the design due to its low inertia characteristics. This allows the fastening loads to be resolved right inside the head to reduce the size and weight of the supporting machine structure which in turn increases accuracy and reliability.

ACKNOWLEDGMENTS

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REFERENCES

1. ‘Low Voltage Electromagnetic Riveting’ - Aerofast Paper #AD86-680, Peter Zieve, 21Oct1986
2. ‘Advanced EMR Technology’ – Aerofast Paper # 922408, Peter Zieve, et al, 13October1992
3. ‘Qualification of EMR for Swaging Collars on the 787’ – John Hartmann, Tim Brown, Peter Zieve, Mark Woods, 3September2005

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