E7000 High-Speed CNC Fuselage Riveting Cell

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ABSTRACT

Electroimpact has recently produced a high-speed fuselage panel fastening machine which utilizes an all-electric, CNC-controlled squeeze process for rivet upset and bolt insertion. The machine is designed to fasten skin panels to stringers, shear ties, and other internal fuselage components. A high riveting rate of 15 rivets per minute was achieved on the first-generation E7000 machine. This rate includes drilling, insertion, and upset of headed fuselage rivets. The rivets are inserted by a roller screw-driven upper actuator, with rivet upset performed by a lower actuator driven by a high-load-capacity ball screw. The rivet upset process can be controlled using either position- or load-based feedback.

The E7000 machine incorporates a number of systems to increase panel processing speed, improve final product quality, and minimize operator intervention. The upper riveting head includes automatic tool changers for drills and upper anvils, both designed with very fast tool changes as a primary goal. The machine also includes fastener verification laser curtains to ensure the fastener being inserted is the correct type and length, and oriented properly. The system has automatic calibration functionality to calibrate normality and stringer tracing sensors, as well as upper and lower die lengths. Additionally, an automatic machine vision system provides high-speed, high-accuracy part resynchronization across a wide range of surfaces for improved local accuracy.

The E7000 automated fuselage riveter is a fast, robust and flexible system that can be used to fasten a wide range of fuselage panels, while improving reliability and final product quality.

INTRODUCTION

In 2012, Electroimpact designed and built the first E7000 series fuselage panel riveting machine for Turkish Aerospace Industries. This is Electroimpact's first automatic riveting for metallic fuselage panels. The system was designed around A320 and A400M fuselage panels, and utilizes unique kinematics to enable automatic fastening accessibility at high angles of curvature. Emphasis has been placed on increasing the "floor-to-floor" rate – not just maximizing fastening speeds – and on ease of maintenance. The machine incorporates many innovative design features to help achieve these goals.

MACHINE STRUCTURE

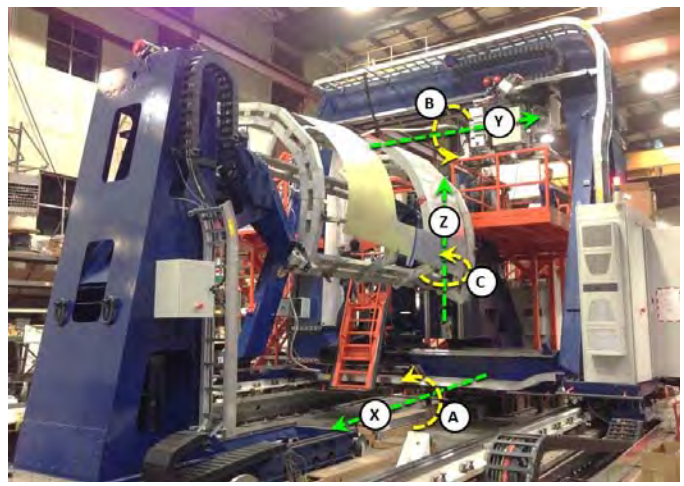

Figure 1. Overall machine structure and axis orientations

The machine gantry carries upper and lower independent heads. The heads traverse the gantry in the Y-direction, while the gantry itself drives in the X-direction. The upper head includes the drill spindle, resynch camera, and fastener driver, while the lower head provides clamping and rivet upset force.

A set of access platforms mounted to the machine allow easy access to the upper head at any position in the cell, without necessitating a return to the park zone. This is in line with the design goal of minimizing overall panel build time, but these platforms also serve another purpose: they provide an optimum position for the fastener feed rack. The rack is placed as close as possible to the upper head for very fast feed times.

UNIQUE FEATURES

The E7000 fuselage riveter incorporates a number of unique features which are designed to reduce overall panel processing time and simplify machine operation and maintenance.

X-axis Struts

The machine is braced in the X-direction by a pair of struts (see Figure 2). This permits faster X-axis accelerations during pitch moves, without the need to wait for vibrations to damp out before beginning a cycle. The result is faster pitch moves and thus a higher rate of fastener installation. One-inch (25 mm) pitch moves of less than 0.5 seconds are typical.

Figure 2. Struts allow more aggressive acceleration and deceleration in the X-direction, reducing cycle time

Part Positioning System

Traditional riveting machine part positioners use a large, welded steel "picture frame" to carry the work piece and its associated tooling. In the typical axis layout, part rotation in the B-direction (around the Y-axis) is achieved passively through differential Z-axis positioning at the two towers. This results in a change in the X-directional component of the structure length, which is taken up by a passive linear bearing arrangement. However, the presence of the picture frame obstructs access to edges of panels at high angles of rotation due to collision between the frame and the lower fastening head structure (see Figure 3). Therefore, a concept was developed to enable part-holding without the use of such a large supporting structure.

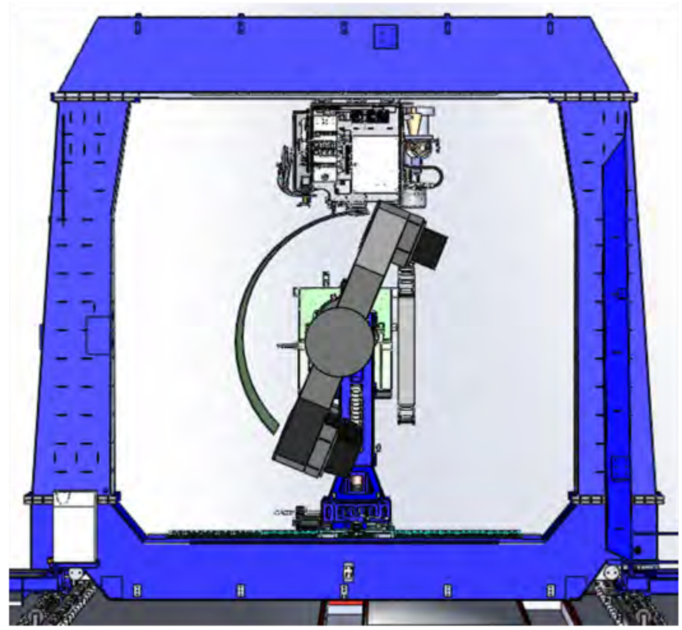

Figure 3: Collision of the picture frame with the lower head would obstruct machine access near panel edges

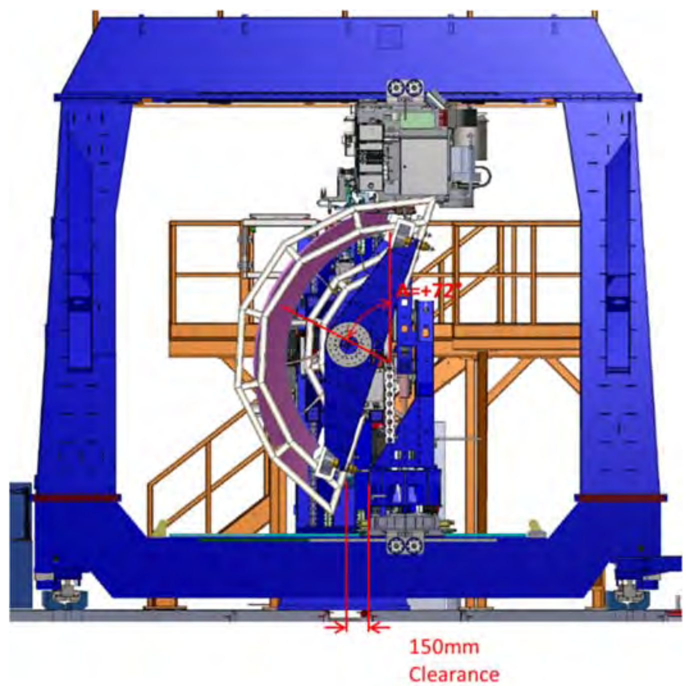

Figure 4. E7000 machine accessing the edge of a panel that spans 144° of curvature

The E7000 part positioner concept eliminates the need for a picture frame. A very light and low-profile dedicated part frame is used, which prevents collisions of the frame with the lower machine head at high A-axis rotations. Consequently, interferences between the part-holding structure and the machine are minimized. The E7000 is able to easily access and fasten all parts of A320 fuselage panels that span 120°, and in fact is theoretically capable of accessing the edge of a panel that spans over 150°. This advantage does come at a cost: because the low-profile dedicated part-holding frame is not as stiff as a conventional picture frame, it is necessary for the positioner to provide moment support in the B-direction to prevent the frame and part from sagging excessively under gravity load. Thus, all of the positioner axes must be servo-driven on the E7000 – no passive axes are used.

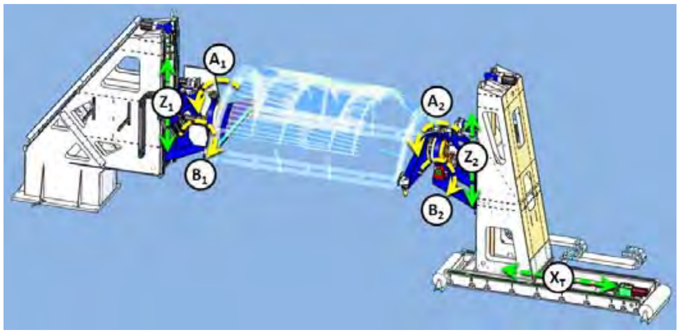

Figure 5. Positioner axis layout

As an added benefit, by removing the picture frame, the moving mass is greatly reduced. The total weight supported by the positioner is in the hundreds of kilograms for most parts, as opposed to several tons for a traditional part positioner. The low supported mass eliminates the need for counterbalance mechanisms and allows for smaller gear reductions, faster axis accelerations, and improved accuracy.

As with the traditional design, there is a change in the X-directional component of length during B-axis rotation. In the E7000 system, this is controlled through a servo X-axis on one of the positioner towers, rather than a passive axis. The lightweight part holding frames are not designed to transmit load associated with moving a passive axis, so this movement must be commanded. B-axis rotation is therefore accomplished by coordinated movement of five servo axes – the two Z axes on each tower, the two B axes, and the tower X axis.

The presence of an X-axis under one positioner tower also serves another purpose – it allows the positioning system to accommodate a range of different panel lengths, while keeping the towers only as far apart as is required for the particular panel being processed (see Figure 6). This is especially useful when both short, high curvature panels and longer, more cylindrical panels are to be processed by the same machine, because large B-axis angles can be achieved for the shorter panels without requiring very tall positioner towers.

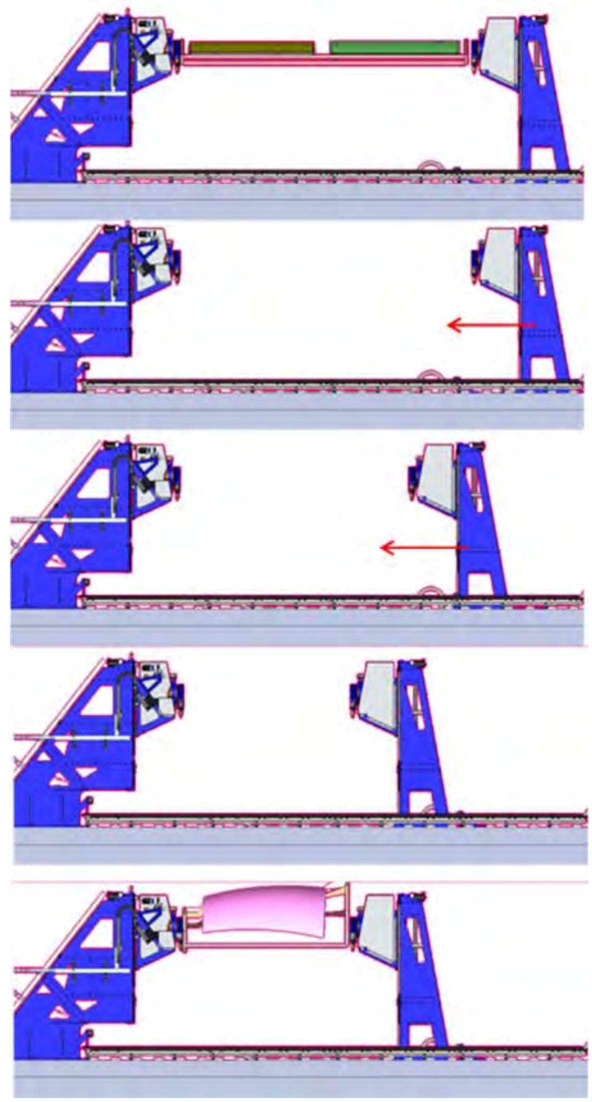

Figure 6. Part positioner tower moves to accommodate different panel lengths

In order to accommodate part loading, conventional CNC riveting machines either require extra Y-axis travel so that the riveter can be moved clear of the positioner frame (a common approach used in the design of C-frame riveters), or extra length between the positioner towers so that the machine can be driven far enough to one side to allow overhead crane access for loading the longest parts. The former results in a wider cell footprint, while the latter requires a longer picture frame than would otherwise be necessary. The E7000 solves this problem with a notch designed into the base of the fixed positioner tower (see Figure 7). The lower beam of the machine gantry passes into the notch, and the gantry passes over top of the positioner tower itself, opening up the part to overhead crane access. This solution is the best of both worlds – the cell footprint is kept small, and the moving mass of the part positioner is kept to a minimum.

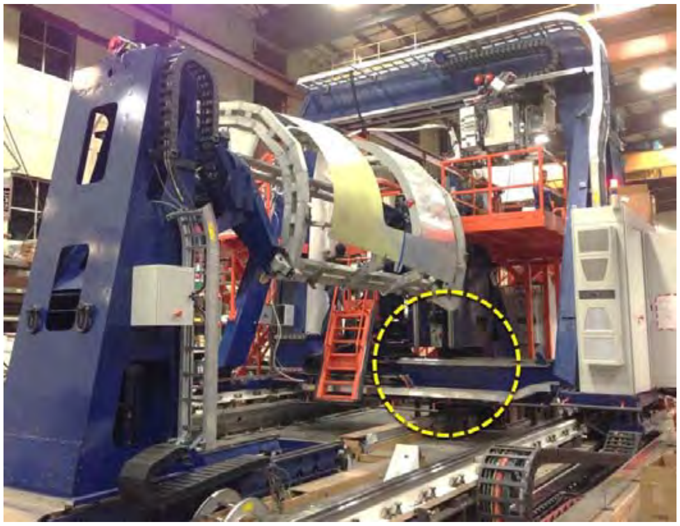

Figure 7. Machine parked, showing the lower beam tucked under the notch in the fixed positioner tower

While the machine is in the park zone, a cantilevered platform provides excellent access to all sides of the upper head (see Figure 8). This platform is the primary means of access to the process tools on the upper head for maintenance. The opposite end of the platform provides an ideal location for a stand to support coupons and a calibration plate (see Figure 9). The upper and lower heads can be de-coupled, allowing the upper head to be moved freely back and forth between the maintenance area and the coupon/calibration area while the machine remains in the parked position.

Figure 8. Upper head positioned over the maintenance area of the park zone platform

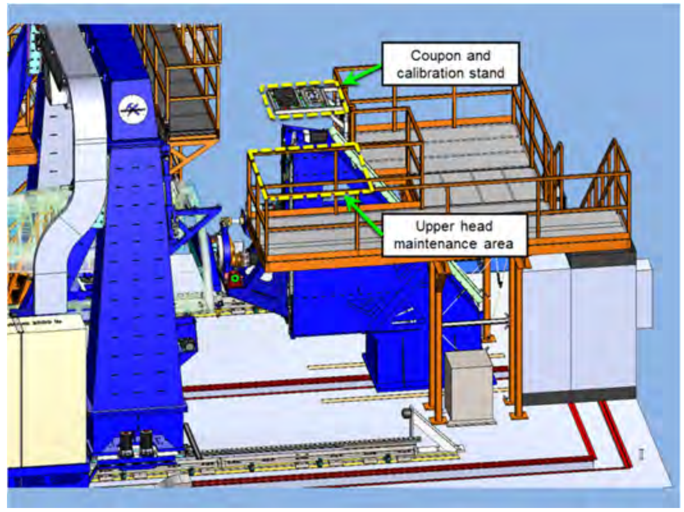

Figure 9: Park zone platform layout

Open Upper Head Design

When designing the E7000 machine, particular attention was paid to the accessibility and maintainability of the upper process head. The upper head is the most complex part of a riveting machine, and while a high cycle rate is certainly an important factor when attempting to increase panel processing speed, an increased cycle rate may not make a big impact on the machine's productivity if downtime is prolonged because components are difficult to access for maintenance or repairs. With this in mind, the upper head was designed with an entire side completely open (see Figure 8). All of the process tools are directly accessible without having to remove hardware. In the event that the spindle or fastener driver must be replaced, the entire process tool assembly can be disconnected and removed quickly and easily from the open side of the head. This is accomplished by moving the upper head over the maintenance platform and using a hydraulic lift cart to aid removal and installation.

Automatic Tool Changers (ATCs)

Another major area of innovation is the automatic tool changing systems. Tool change for the drills and upper anvils is accomplished using two separate systems mounted on opposite sides of the upper process head. This eliminates the need for a complex tool change mechanism that can access both the drill and driver. The resultant tool changer designs are greatly simplified, with few moving parts, and the process of changing tools with these mechanisms involves a minimal number of steps and is thus very fast. Drill changes are achieved in about 12 seconds, while upper anvils can be changed in less than 7 seconds. A complete automatic upper tool change sequence, including drill change, cutter length measurement, and upper anvil change, is achieved in under 30 seconds.

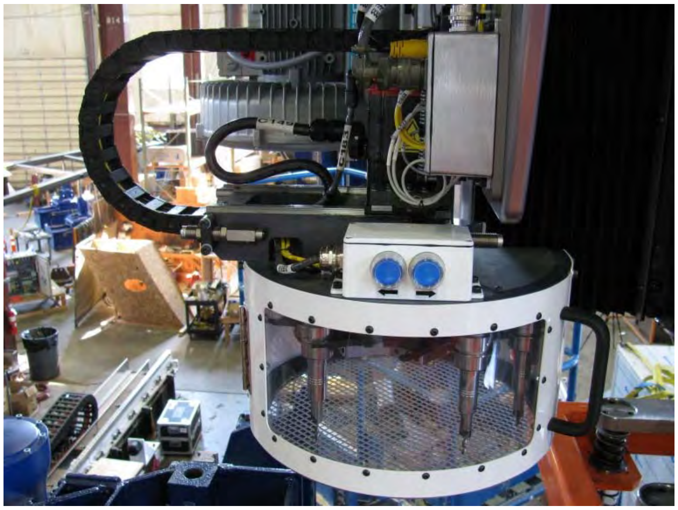

Figure 10. Drill ATC

The drill ATC is a very simple and robust design which consists of one servo-controlled turntable and one air cylinder-actuated linear slide. The drill ATC holds 12 HSK-40 tool holders using passive spring-steel grippers. To perform a drill change, the air cylinder slides the ATC into the tool change position, and the tool shuttle moves to engage the active tool in the spindle with an empty gripper on the ATC. The tool holder snaps into the gripper and is held firmly. At this point, the spindle drawbar disengages the tool, the spindle is retracted, and the ATC turntable rotates to position the new cutter under the spindle. The spindle then engages with the new tool and the tool shuttle moves away from the ATC, disengaging the tool from the gripper. Finally, the ATC is retracted, the cutter length is checked, and the new tool is ready to use. The entire process is accomplished using just two moving parts on the ATC (the turntable and the slide) and two of the axes on the upper head (spindle feed and tool shuttle), which is greatly simplified compared to traditional ATC designs which rely on an articulated arm to transfer the tools between the spindle and tool storage rack.

Figure 11. Injector-mounted automatic anvil tool changer

The upper anvil tool changer is integrated into the rivet and bolt injector rack (see Figure 11). The anvil tool changer takes advantage of the fact that the injector rack shuttles to align the appropriate injector with the fastener driver. Each anvil is mounted to its corresponding injector using an air-opened, sprung-closed gripper. To perform an anvil change, the driver is shuttled to the inject position and the gripper is closed firmly around the base of the anvil. The driver then disengages from the anvil by retracting, leaving the anvil behind in the gripper, and the injector rack moves to line up the new tool and injector. Instead of an HSK-style interface for the upper anvils, a custom interface was designed which uses passive ball spring plungers in the socket of the fastener driver to retain the anvil. This passive tool engagement is possible because the anvil only requires compressive and radial support during bolt insertion and rivet upset. Although the anvil is held quite securely in the driver socket during normal operation, it takes less than 10 pounds of force to remove it. The passive anvil retention mechanism not only reduces the complexity of the driver process tool, but also allows for much faster engagement and disengagement with the socket than would be possible with an active mechanism.

The E7000 machine built for Turkish Aerospace Industries is particularly unique in that the sealant inserter tip does not need to be changed when switching between fastener types or diameters. A compliant sealant inserter tip was designed that is able to apply sealant to the countersinks of multiple fastener diameters and types. Thus, performing a full upper head tool change is truly automatic – it can be completed with no operator intervention, and without driving the machine back to the maintenance platform.

Machine Auto-Calibration and Coupon Holder

Another way the E7000 machine speeds panel processing times is through automatic calibration of process tools. A stand is mounted on the operator platform which holds a plate with machine calibration features. This stand also contains a space for holding a coupon.

The first step of the auto-calibration routine involves driving to a resynch target on the calibration plate. The machine uses the resynch camera to synchronize on this target. The position of each calibration feature is programmed relative to this target, so the machine can now drive to each feature with a high degree of accuracy. The auto-calibration plate contains features for calibrating the following process tools:

- **Normality sensors:** The upper process head contains four laser normality sensors for normalizing the drill to the panel and setting proper fly height above the panel. The machine clamps up on a thin plate, forcing it into a position that is normal to drill spindle. The CNC then sets the zero point for each laser sensor. This zero plane also becomes the machine fly height when working on a panel under normality control.

- **Stringer laser tracers:** The lower head contains a laser tracer for stringer edge margin feedback. A small bar protrudes from the underside of the calibration plate for calibrating the tracer. The lower head drives to one side of the bar and takes a measurement with the tracer. The C-axis then rotates 180 degrees and the lower ram drives to the other side of the bar and takes a second measurement. Averaging the two measurements allows the tracer to be calibrated with a high degree of accuracy.

- **Upper and lower die lengths:** The machine clamps up on the calibration plate and advances the lower ram until the die touches the plate. The lower clamp-to-die offset is recorded. The upper riveting tool then advances until it also contacts the calibration plate, and the upper clamp-to-die offset is recorded. This process can be repeated for each upper and lower tool to record the die position for each individual tool.

- **Drill length measurement:** The upper pressure plate contains a cutter length measurement device called the "compliant touch-off button." This simple device contains a floating button and a switch. After each drill change, the spindle drives downward toward the compliant touch-off until the tip of the cutter contacts the button and triggers the switch. The overall length of the cutter is then recorded by the CNC. This system provides multiple benefits. First, this serves as a check to ensure the correct tool has been loaded. The measured cutter length is checked against the expected length. If these numbers differ significantly, the operator is instructed to check the cutter. This also allows the drill shuttling height to be set for each tool. It is preferable to keep the drill spindle positioned as low as possible when it is not in use; this minimizes the time it takes to reach the panel and begin drilling, as well as the time needed to retract before shuttling the driver into place, improving cycle time.

The stand used for the calibration plate also doubles as a coupon holder (see Figure 12). A coupon is loaded into the holder and held in place with spring-loaded jaws. The operator is then free to run test cycles. This arrangement eliminates the need for the operator to manually hold a coupon between the heads, which not only reduces strain on the operator, but also greatly improves safety by keeping the operator's hands away from the riveting heads while the machine is active.

Figure 12. Coupon and calibration stand

Flushness Measurement

Another new technology developed for the E7000 riveting machine is the non-contact fastener flushness measuring system, which is located on the process tool shuttle table. A high-accuracy distance-measuring laser is used to measure the height of the fastener head relative to the panel surface.

There are two primary strengths of the laser-based flushness measuring system. First, it is very fast. There is no need to extend a probe down to the panel surface to take this measurement, so it is only necessary for the tool shuttle to align the laser with the fastener and pause for a very brief moment to take the measurement. Second, it has no moving parts. A mechanical probe used for this task would normally rely on some type of high-accuracy linear transducer, such as an optical scale. Extending and retracting a probe with this type of sensitive equipment is likely to create reliability issues. The laser-based measuring system is therefore expected to be far more robust.

Fastener Verification and Panel Protection

A common struggle in the design and operation of riveting machines is ensuring that fasteners are fed correctly and oriented properly before inserting them into the panel. There are many possible reasons that the wrong fastener may be fed, or that a fastener may be fed in the wrong orientation, but it is imperative to catch these issues before damage to the part or the machine itself occurs. Electroimpact aims to design robust mechanical systems to prevent these issues from occurring in the first place, but when they inevitably do occur, the problem must be caught before the fastener gets to the part.

The first line of defense against a "bad" fastener is robust mechanical design. This includes a fastener injector designed to eliminate the possibility of inserting the wrong type of fastener or one that is oriented incorrectly. (This injector design is discussed in detail in a paper by Electroimpact engineer Cosmos Krejci.) The fastener-holding fingers are also manufactured to very tight tolerances to greatly reduce the possibility of a fastener becoming tipped or one fastener becoming stacked on top of another inside the fingers.

The E7000 also employs a number of additional protections against improperly oriented fasteners, one of which is an array of laser curtain sensors (visible in Figure 11). This set of sensors is used to check that the correct length fastener has been fed, and that it is oriented correctly in the anvil's fingers. The first curtain is oriented vertically in front of the injector, parallel to the axis of the fastener. As the fastener is snapped into the fingers, this sensor immediately measures the length. If the length is not correct, the machine automatically runs a purge cycle to eject the incorrect fastener, then feeds a new fastener.

After the fastener length is verified, the tool shuttles to a second laser curtain, perpendicular to the fastener axis, which checks the orientation of the fastener in the fingers. If the fastener is held crooked in the fingers, it is likely to cause damage if the machine attempts to insert it into the hole. The horizontal light curtain automatically finds the centerline of the fastener, and if its position does not fall within the expected range, the machine runs an automatic purge cycle.

When the time comes to proceed with inserting the fastener, prevention of a jammed fastener (a fastener whose tail hits the rim of the hole instead of going in) is accomplished using a mechanism called the "air gap." The socket that holds the upper anvil is free to slide in a bushing on the end of the driver's actuator shaft. A 10 mm gap of air exists behind the socket, held open by a compression spring, with the socket retained by a shoulder bolt. As load is applied to the anvil, the spring compresses and the gap begins to close. Finally, when the gap is fully closed, the full thrust force of the driver can be transmitted through the socket and into the anvil. This means that as the driver is inserting the fastener, there is a 10 mm portion of the stroke between when something stops the anvil from moving – such as the fastener head being fully seated in the hole, or the tail of the fastener jamming into the side of the hole – and when the air gap collapses and allows the driver to apply full force to the fastener. An analog position sensor is attached to the side of the air gap mechanism, monitoring the position of the socket inside the bushing. During the insertion stroke, the machine watches for premature motion of the socket, which would indicate a jammed fastener. If premature motion is detected, the driver immediately comes to a stop before it applies its full thrust force to the jammed fastener and damages the panel.

The final line of defense is a technique widely used in the automated fastening industry. The lower clamp force is provided pneumatically and is typically a few hundred pounds in magnitude. If a fastener jams on its way into the hole, or falls from the fingers and lays down sideways over the hole, and the upper anvil begins to apply its full thrust force to the fastener, the entire panel will begin to move away, pushed by the force of the driver. This causes the lower clamp foot to move unexpectedly. Similar to the air gap mechanism, a linear transducer attached to the clamp foot detects this motion, and the machine halts the cycle immediately to prevent damage to the panel.

With the combination of robust mechanical design of the fastener feed systems, the laser length and orientation checks, the "air gap" protection against jammed fasteners, and finally, the lower clamp push-away protection, the E7000 machine is extremely well-equipped to prevent installation of incorrect fasteners and damage caused by failed fastener insertion.

MACHINE PERFORMANCE

During initial testing, riveting rates of up to 15 per minute were achieved. This includes clamping, drilling, sealant application, rivet insertion and upset, unclamping, and a 1-inch (25 mm) pitch move. Several areas of potential improvement were identified in the process of building and programming the machine. A second generation of E7000 machines is currently in development, and these machines are expected to achieve 10-20% higher rates after these improvements are implemented.

SUMMARY/CONCLUSIONS

The E7000 fuselage panel fastening machine is a fast, reliable, and robust system which incorporates many technological advancements to improve maintainability, productivity, and quality. Aside from a high riveting rate, Electroimpact also focused on the other parts of panel processing, from machine setup to in-process measurements, that help to increase overall floor-to-floor rate. An emphasis was also placed on machine accessibility, ergonomics and maintainability to improve operator and maintenance efficiency.

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DEFINITIONS/ABBREVIATIONS

floor-to-floor rate Fasteners installed per minute, measured from the time the part enters the cell to the time the next part enters the cell. This rate factors in activities that negatively impact machine productivity, such as time spent loading and unloading the part.

ATC Automatic tool changer