An Automated Production Fastening System for LGP and Hi-Lok Titanium Bolts for the Boeing 737 Wing Panel Assembly Line

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Abstract

A new automated production system for installation of Lightweight Groove Proportioned (LGP) and Hi-Lock bolts in wing panels has been implemented in the Boeing 737 wing manufacturing facility in Renton, Washington. The system inserts LGP and Hi-Lok bolts into interference holes using a ball screw mechanical squeeze process supported by a back side rod-locked pneumatic clamp cylinder. Collars are fed and loaded onto a swage die retaining pin, and swaging is performed through ball screw mechanical squeeze. Offset and straight collar tools allow the machine to access 99.9% of fasteners in 3/16″, ¼″ and 5/16″ diameters. Collar stripping forces are resolved using a dynamic ram inertial technique that reduces the pull on the work piece. Titanium TN nuts are fed and loaded into a socket with a retaining spring, and installed on Hi-Loks Hi-Lok with a Bosch right angle nut runner. Bolt installation and collar swage heights and loads, as well as nut torque values are captured and logged for future reference.

Introduction

The Panel Assembly Line (PAL) is a new machine cell in Renton, WA consisting of eight E6737 automated mechanical ball screw squeeze riveting machines on four assembly lines. The machines are used to fasten aluminum stringers to the upper and lower skin panels for the Boeing 737 aircraft. Each machine is capable of installing aluminum rivets as well as titanium LGP and Hi-Lok fasteners.

The original 737 wing panel fastening machines use a servo hydraulic method to drill and fasten tacked wing skin panels and stringers in a horizontal configuration. The panels are first tacked together with temporary fasteners in a build fixture and then transferred to the automated machine via overhead crane. Once on the machine aluminum rivets are installed and holes are drilled and left open for bolt installation. When the machine is finished, the panels are transferred via crane to a third cell where titanium lock bolts and threaded Hi-Loks are installed.

Figure 1. PAL machine with tooling fixture loaded at Electroimpact

In the new PAL cell, the stringers and skins are loaded into a precision locating fixture designed to allow the PAL machines to work without previous manual tack fastener installation. The machines install aluminum rivets as well as titanium LGP lock bolts and Hi-Lok threaded fasteners in three diameters. Because the machine is capable of automated installation of not only rivets, but also titanium fasteners as well as collars and nuts, many hours of manual labor can be saved over the hand installation method.

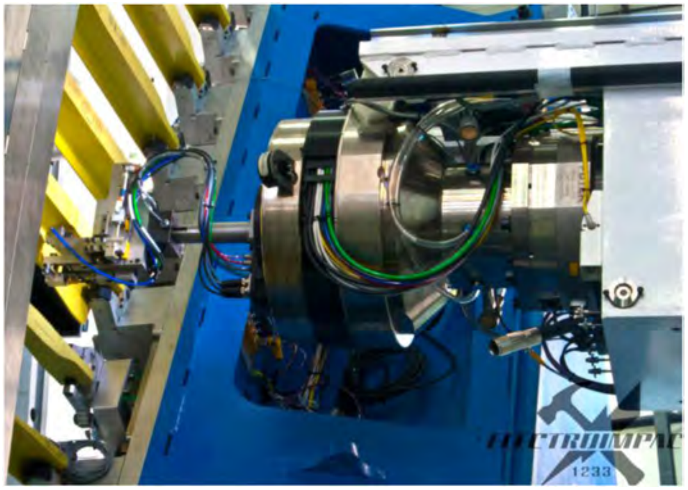


Figure 2. PAL machine navigating 737 stringer with offset tool installed at Electroimpact

System Overview

The bolting process begins when the two aligned machine heads apply a clamp load to the stringer/skin stack-up. The load is applied by a pneumatic cylinder on the stringer side. A load of approximately 3,500 N closes the gap between the stringer and skin, and prevents shifting and the formation of burrs between the parts while drilling. After the hole is drilled and measured by a hole probe, a titanium bolt is fed pneumatically to the feed fingers of the skin side driver. A rod lock is applied to the stringer side pneumatic clamp cylinder to react the installation force of the interference fit titanium fastener. The rod lock prevents transfer of the installation force into the skin and stringer indexes and clamps.

Figure 3. Stringer side process head with clamp cylinder rod visible in center

Bolt seating is accomplished using a torque skip function which limits the amperage output for the bolt driver axis. Seating force can be varied by the grip and type of bolt by altering the maximum amperage output of the driver axis accordingly. Bolt seating is verified by the linear scale on the driver axis.

LGP collars are loaded into a vibratory bowl and conveyed pneumatically in small batches of 10-20 down a rectangular tube to a buffer assembly. When the stringer side collar swaging anvil is ready, a single collar is escaped from the buffer and is pneumatically transferred down a rectangular tube to a loading mechanism that presents the collar to the machine axis in-line with the collar die.

Figure 4. LGP collar and TN nut feed path shown with buffers and vibratory bowls

With the collar pneumatically held in position against spring loaded locating fingers inside the load mechanism, the swaging ram is advanced via the active ram until a pin located in the center of the die enters the hole in the collar. The active ram is a device that uses air pressure to extend the swaging ram and die relative to the rest of the anvil, and is beneficial because it imparts an order of magnitude lower forces in order to prevent damage to the loading mechanism and the work piece in the event of a collar miss-feed.

When the collar is loaded onto the die pin, the collar loader moves out of the feed position, stripping the collar through the spring loaded locating fingers and leaving it on the die pin. After the lock bolt has been installed in the hole, the rod lock releases, and the stringer side table advances the collar ram with the active ram extended until the die pin engages the bolt tail. If the collar is successfully loaded onto the bolt tail, the active ram switch will be actuated. If the collar is unsuccessfully loaded or a cocked collar jams on the bolt tail, the active ram cylinder will be pushed back and fail to actuate the switch. This allows the machine to identify an error before attempting to swage the collar onto the fastener tail.

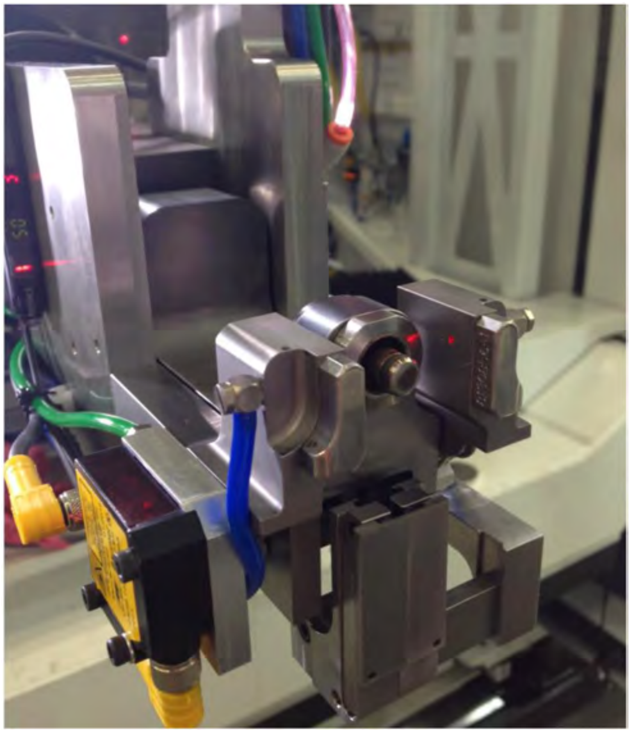


Figure 5. Offset collar anvil with active ram extended and loader visible below

If the collar transfer to the bolt tail is successful, the ram continues to advance toward the stringer, the die mouth engages the end of the collar, and begins to swage. Collar swage height is calculated using pin protrusion, which is inferred from fastener length and panel stack as measured by the clamp cylinder's integrated scale. Once the swage height is determined, the cylinder scale is used to obtain the ram position required to reach the desired swage height.

After the swage is complete, the die is stripped off of the collar by rapidly retracting the stringer side process head. During the retract, the active ram cylinder functions as an inertial slide hammer, applying an impulse to drive the swage die off of the formed collar, reducing pull on the work piece. This technique is used in tools designed to access both straight and offset fastener positions.

The innovations and advantages of this system have helped reduce the cycle time for LGP fasteners to as low as 6.8 seconds, or the rate equivalent of approximately 8.8 collared bolts per minute.

The PAL machine also installs titanium TN nuts. Nut runner anvils are similar to collar swaging anvils, but with an integrated Bosch tightening spindle which has a spring loaded splined shaft. A 12-point socket with a circular spring clip retaining mechanism is mounted to the shaft.

Similar to collars, nuts are loaded into a vibratory bowl and pre-fed to buffers on the end of the stringer side table. Also similar to a collar, a nut is escaped and pneumatically conveyed down a rectangular tube to a loader with spring loaded locating fingers designed to position the nut in front of the nut runner socket. The socket is then advanced to pick up the nut while the Bosch spindle performs an ‘amble’ routine, rotating back and forth to help the nut and socket engage. The socket has engaged the nut when the socket reaches a programmed position as measured by the clamp cylinder scale.

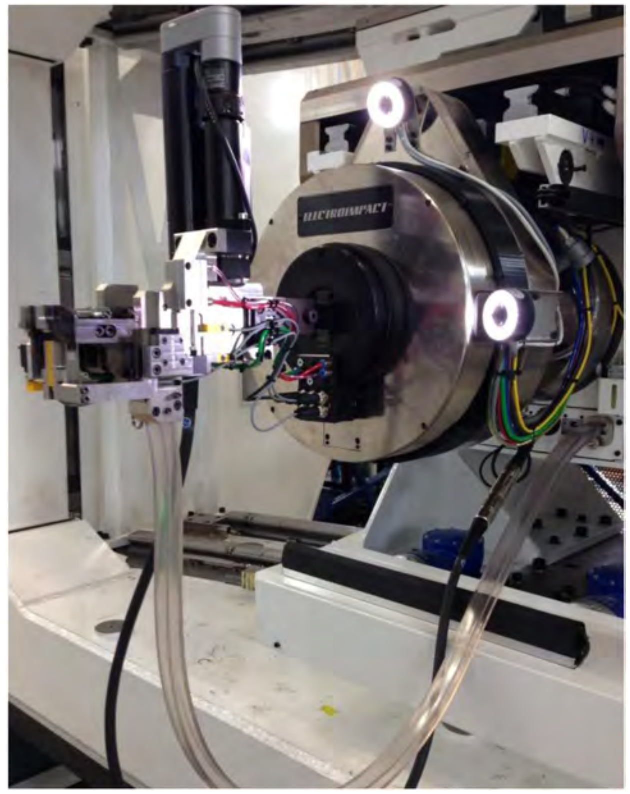


Figure 6. Nut runner anvil installed on PAL machine at Electroimpact

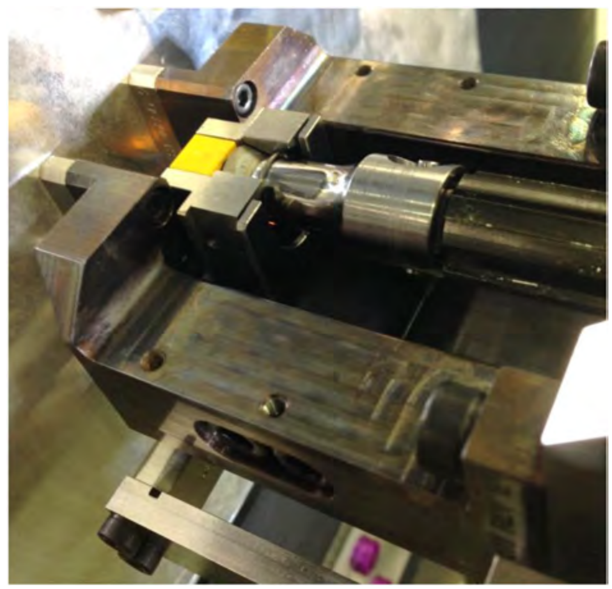


Figure 7. Nut runner socket engaging nut in loader

When the socket reaches the programmed position, the rod lock is actuated as the nut loader is retracted, leaving the nut retained in the socket. After the threaded Hi-Lok bolt is pressed into the interference hole, the rod lock is released and the nut runner socket begins spinning while advancing toward the bolt tail. The socket advances until the spindle's splined shaft is compressed enough to complete the rundown. The socket is then spun to the desired torque using a multi-step torqueing process, which utilizes a faster rundown speed as well as a slower final torqueing speed.

See the Sequence of Operation section for more detailed fastening cycle breakdowns.

Comparison With Existing Systems

Unique features of this system include:

1. **Central die pin:** The offset collar tool employs a spring loaded die pin to transfer the collar from the feed tube mechanism onto the end of the bolt tail. Collars are retained on the pin by means of a consumable rubber o-ring. The die pin is sprung forward with enough force such that the o ring can slide into the collar but not enough to damage the collar feed tube mechanism. During swage, the die pin spring is compressed as the bolt pushes the pin out of the collar. After swage, the pin returns to its sprung forward position for the next cycle.
2. **Active ram:** The active ram is a technique that allows the machine to pneumatically extend the collar ram relative to the clamp pads and has several benefits which other machines require servo axis movement to achieve.

a. Cycle time is reduced because the machine is able to load collars with no machine axis or clamp cylinder movement. Thus, the machine can load collars while drilling without risking hole quality, and while inserting bolts without damaging the rod lock.

b. Offset collar forming can be done in very space limited applications. Active ram allows the machine to retract off of the panel while under a very low offset stringer flange, because when the active ram is extended, the size of the portion of the anvil underneath the offset string flange is reduced as shown in figure 8 and figure 9.

c. The active ram can only impart a maximum force of 500N, thereby protecting the feed mechanism from damage in the event of miss-feed. The 500N force limit can also prevent the machine from attempting to swage a collar if it is miss-fed, or “cocked” onto the tail of the installed lock bolt.

d. The load required to strip the swage die from the collar after installation is reduced, because the active ram functions as a slide hammer during quick servo retract moves.

Figure 8. Offset collar tool with active ram extended

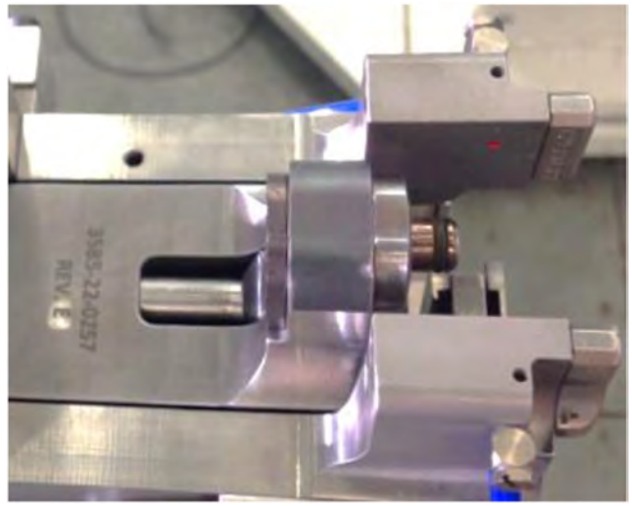


Figure 9. Offset collar tool with active ram retracted

3. **Pneumatically actuated rod lock:** Insertion of interference bolts requires more load than is provided to clamp the work piece during cycles. The rod lock provides a very fast way for the machine to make the stringer-side clamp feet rigid, preventing panel marking and damage to nut and collar feed mechanisms.

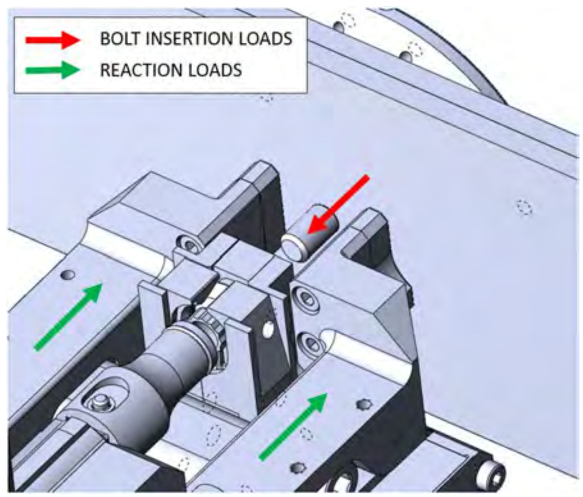


Figure 10. Bolt insertion reaction loads

4. **Nut runner anvils:** Compact, detachable nut runner anvils provide nut installation capability in a package similar in size and shape to a collar forming anvil.
5. **FANUC 30i-B CNC with the Pressure and Position Control**: With existing CNC systems, load cells are treated as generic input to the IO system and are converted to a digital value with an input module, transferred over a fieldbus to a PLC, and then converted to a calculated load before the data is available for capture and analysis. The FANUC CNCs used by the PAL machines receive load cell signals directly into an Analog Monitoring Unit (AMU) which is part of the FANUC Serial Servo BUS (FSSB). This improves reliability and speed of data capture.

6. **Absolute linear magnetostrictive clamp cylinder position feedback:** Many systems use an analog linear encoder for cylinder position measurement. The low voltage or amperage signals from these sensors are subject to noise from various sources such as 600V servo motors. As the length of these cylinders increase, the usable encoder resolution decreases because the analog input module has a fixed counter size to represent the span of the analog signal. PAL uses a magnetostrictive linear encoder which measures the cylinder position using the time of flight for a magnetic pulse sent along the sensor shaft. The resulting position measurement is absolute and ideal for operation within a noisy environment, because the signal is immediately transformed into a robust Synchronous Serial Interface (SSI) signal. The system is minimally affected by electromagnetic interference and is linear to as low as +/− 50 microns.

Bolt Cycle Analysis

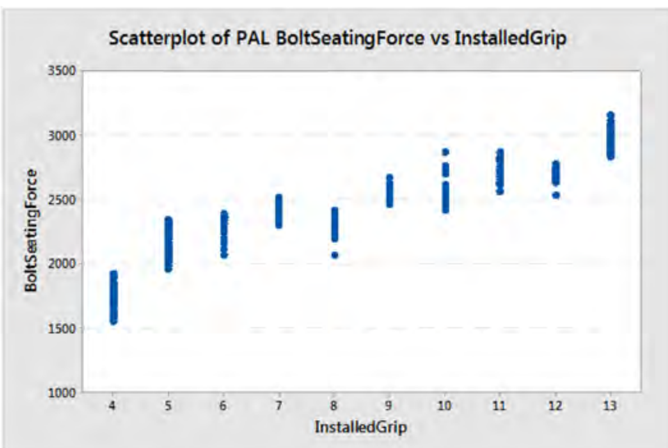


Figure 11. Bolt Seating Force vs. Installed Grip

An advantage of using a ball screw, over the previously used pneumatic bolt seating system is an added ability to capture seating force using a load cell. This information can be used to help with process diagnosis.

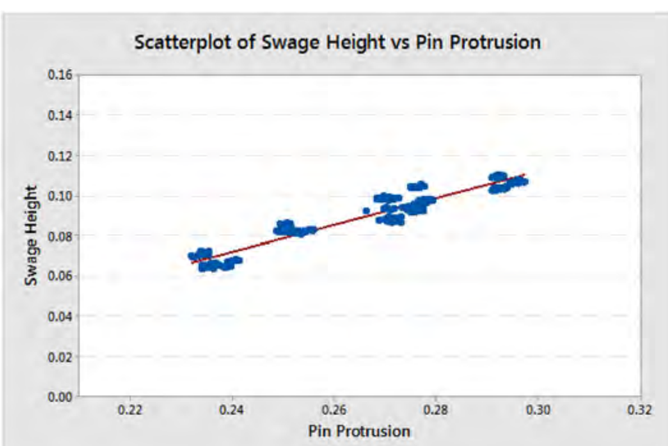


Figure 12. Collar Swage Height vs. Bolt Pin Protrusion

Using the magnetostrictive linear encoder, position for desired swage height can be determined, and driven to. This allows for a precise desired swage height for any given pin protrusion.

Summary/ Conclusions

The Boeing Panel Assembly Line and its machines help increase rate through automation using a number of techniques developed to decrease cycle time and reduce damage risk to parts. PAL also enables increased automation through installation of LGP bolts, Hi-Lok bolts, nuts, and collars which previously required manual labor.

Bolt Installation Innovations

1. Titanium fasteners are installed with a servo ball screw drive actuator
2. Installation loads are reacted by a back side rod locked air cylinder
3. TN nuts are installed using compact and interchangeable anvils

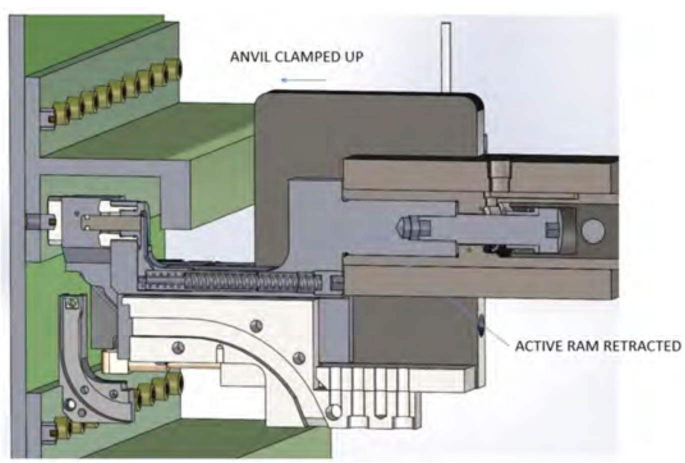
Collar Installation Innovations

1. Active ram is used to reduce cycle times and protect feeding hardware and stringer from damage
2. Offset collar tools employ a central die pin to improve transferring collar onto bolt tail
3. 99.9% of all LGP collar positions are accessible by the automated machine, because active ram permits machine access to very tight offset stringer locations
4. An integrated mag cylinder linear encoder improves the accuracy of the calculated collar swage height.

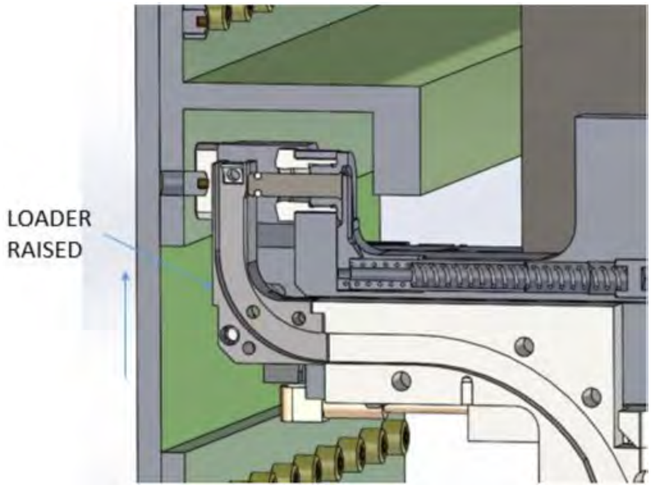
Sequence of Operation

The processes of collar and nut installation are broken down as shown in this section.

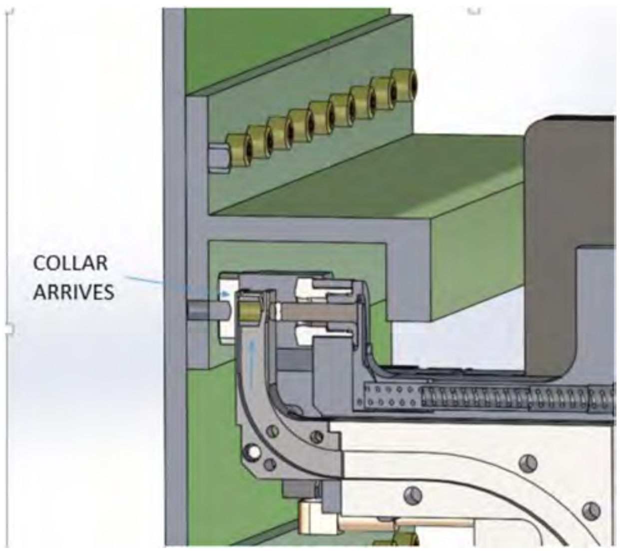
Bolt and Collar Cycle Breakdown



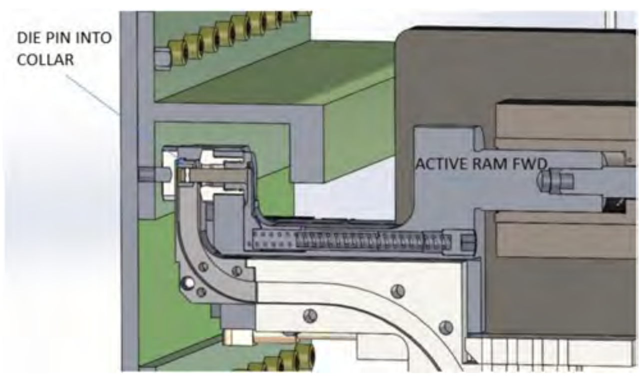
Collar Cycle Step 1. Anvil clamp up, active ram retracted



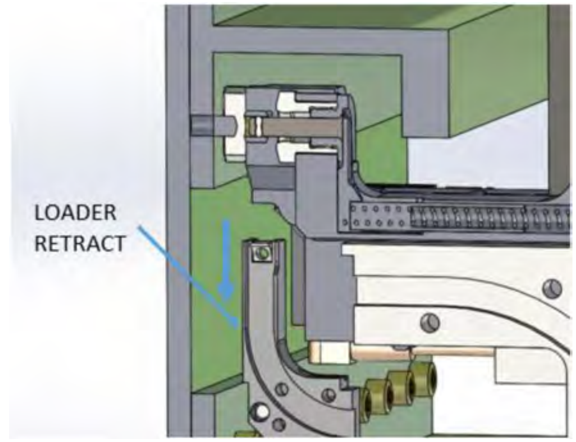
Collar Cycle Step 2. Loader raised



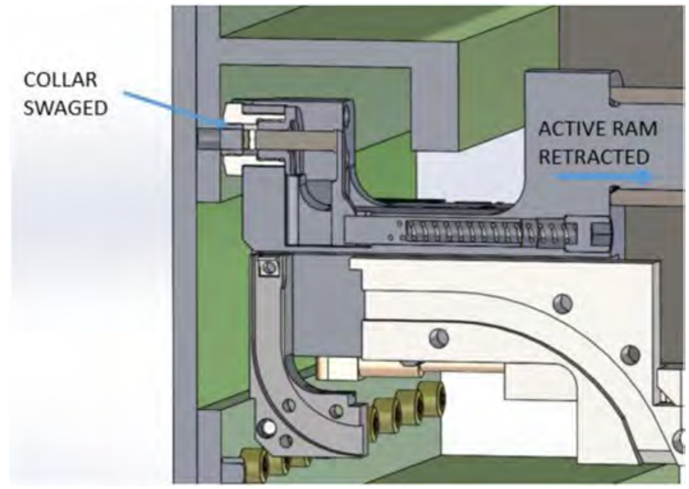
Collar Cycle Step 3. Feed collar



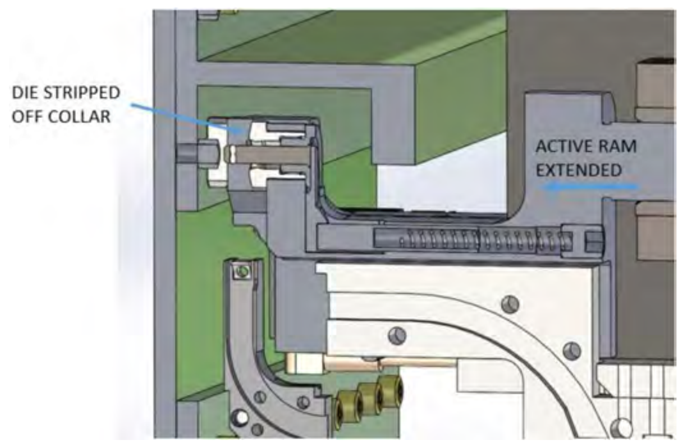
Collar Cycle Step 4. Die pin extended into collar



Collar Cycle Step 5. Loader Retract

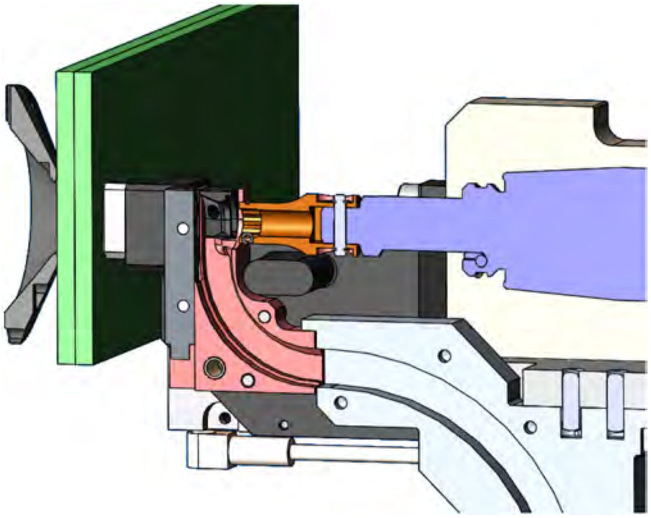


Collar Cycle Step 6. Collar Swaged

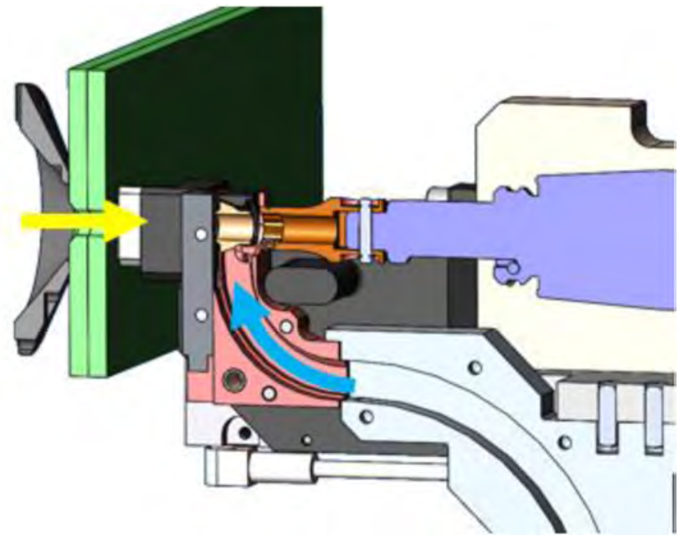


Collar Cycle Step 7. Die Stripped off Collar

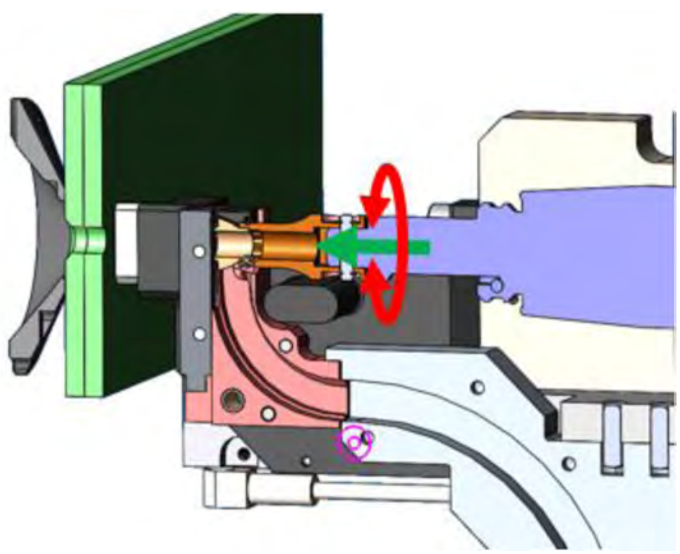
Bolt and Nut Cycle Breakdown



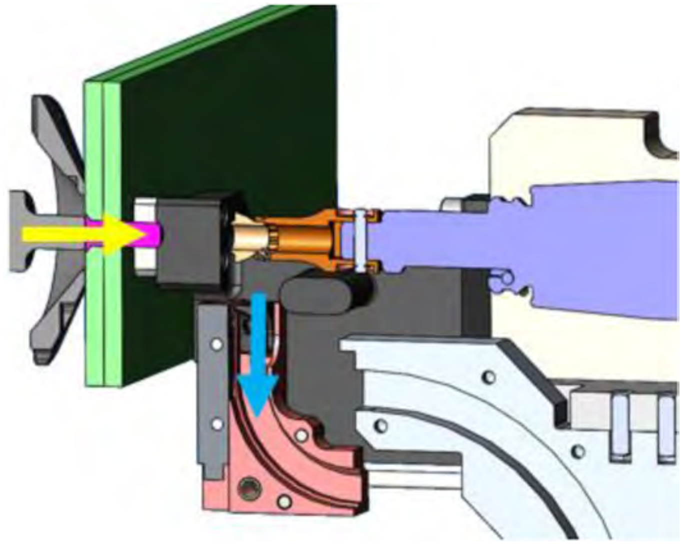
Nut Cycle Step 1. Clamp up.



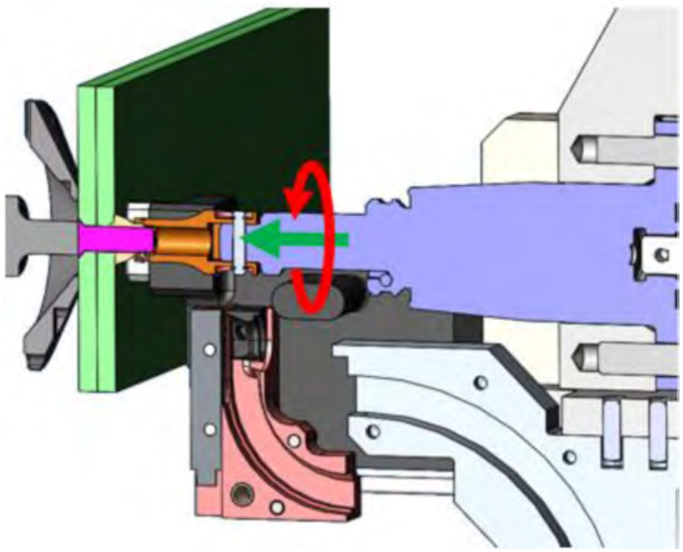
Nut Cycle Step 2. Drill and countersink hole, feed nut.



Nut Cycle Step 3. Machine drives forward while spindle performs amble routine, engaging 12-point pattern with socket and retaining spring. Rod lock is actuated while bolt is fed.



Nut Cycle Step 4. Socket strips fastener from loader fingers as loader retracts. Hi-Lok is inserted and rod lock is released.



Nut Cycle Step 5. Spindle runs nut down Hi-Lok threads and torques to specification. Machine unclamps.

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