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Rivet Quality in Robotic Installation

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ABSTRACT

The concentric technology drill, insert and upset end effector opens up new avenues of riveting automation. A complete riveting cycle can be performed through a continuous clampup with a compact end effector. The drill motor is placed in the center of the electromagnetic riveting head. This eliminates the requirement for a bulky shuttle mechanism. Proposed applications for this technology are discussed. Aerospace companies have been concerned about the certification of rivets formed with the electromagnetic impulse process. Electroimpact now has both interference and fatigue results from tests independently performed by several aerospace companies. The results are quite favorable if the correct forming parameters are employed. These results are presented to the extent that release can be secured from the sponsoring companies. Electroimpact also has an in house fatigue testing capability which supplements the test results. For example flat forming dies yield inadequate interference and mediocre fatigue results. The use of cupped forming dies is extremely preferential when employing this process. The process variables which must be controlled when employing the Electroimpact process are outlined.

INTRODUCTION

The significant increase in demand for aircraft in the late 1980's has led aircraft manufacturers to look for means of increasing production speed. In addition the Aloha Airlines accident has increased the awareness of fastener fatigue. Electromagnetic riveting systems provide solutions in these two areas. The lightweight and low recoil of the Low Voltage Electromagnetic Riveter (LVER) allows use of robots or positioners considerably lighter than required by hydraulic squeeze presses. The LVER drill/insert/rivet (DRID) end effecter weighs a mere 25 lbs. and has a recoil force of under 75 lbs when upsetting 3/16" diameter rivets. A drill operates through the center and is concentric with the riveting head allowing a complete riveting cycle to be performed under a continuous clampup without the need of a bulky shuttle mechanism or tool changer. This opens up new avenues for assembly of complex structure such as wings and body panels since the tool can be easily moved through the part rather than the conventional cumbersome method of moving the part through the tool.

The LVER technology has also been adapted for use as a handheld tool (HHER). Designs range from an eight-pound actuator for 3/16" rivets. Two HHERs are positioned on either side of the rivet and fired simultaneously. This technique allows installation of slug rivets by hand, a function which is not possible with existing technology except in limited positions.

Aerospace companies have been concerned about the certification of rivets formed with the electromagnetic impulse process. Interference and fatigue tests have been performed independently by several aerospace companies. The results to date are quite favorable showing an increase in fatigue life in nearly all cases provided the correct forming parameters are used. These results are presented to the extent that release has been secured from the sponsoring company.

THEORY

Two actuators are typically employed, one located on each side of the rivet. Each actuator has its own capacitor bank and silicon controlled rectifier switch (SCR) as shown in Fig. 1. The capacitor banks can be charged to the same or slightly different voltages. The SCRs can be triggered simultaneously or with a small delay.

The mechanism of force generation in the LVER (Low Voltage Electromagnetic Riveter) is eddy current repulsion. A copper pancake coil is held in close proximity to a copper driver plate. The device is fired by triggering an SCR which discharges a bank of capacitors through the coil. A current on the order of 10,000 amps flows through the coil creating a large local magnetic field. Eddy currents are induced in the adjacent driver plate, which results in a repulsive magnetic force. This force accelerates the driver toward the workpiece. Peak forces of over 30,000 lbs can be reliably and accurately generated from a 3.5” diameter coil. Electromagnetic riveting has been used by at least two aerospace companies in the past [1,2,3]. These older systems however operate at voltages on the order of 10 kVDC resulting in inherently dangerous and high maintenance machines. The LVER, as the name implies, operates at a much safer maximum voltage of 500 VDC. Typical voltages for 3/16” diameter rivets is under 300 VDC. Electrolytic capacitors are employed to provide a compact energy storage bank at this low voltage.

Eddy current repulsion is inherently transient. The duration of the pulse in the LVER machines is on the order of 1 msec. The narrow output force pulse permits the transfer of momentum to a recoil mass which is slowly decelerated resulting in only a minimum recoil force. The peak recoil force is typically two orders of magnitude lower than the peak force of the driver. For example, the peak force upsetting a 3/16” diameter 7050 rivet is on the order of 5,000 lbs, which results in approximately 75 lb peak force felt by the mounting structure. This can be reduced even further by the addition of a greater recoil mass.

Unlike previous electromagnetic riveting systems the LVER employs separate capacitor banks for each of the two opposing actuators. This eliminates the requirement for a long pulse cable to connect the two actuators in series. In the LVER a pulse cable of from 10 ft to 20 ft long is typically employed to connect the capacitor banks to the coil on each side.

Since the force generation of the LVER is of electrical origin opposing actuators can be fired synchronously or with a small delay. The rivet is therefore formed from both sides resulting in more uniform hole fill than that obtained with conventional upset methods. In addition the electronic controls allow simple tailoring of the force pulse to a specific application for both slug and headed rivets.

APPLICATIONS

Significant strides in the development of LVER based systems have taken place since their introduction at the FASTEC ’86 conference [4,5]. A number of systems have been constructed from bench top riveters to complete drill/insert/upset end effecters. The technology has also been adapted into a handheld configuration with models ranging from 8 lb units capable of upsetting 3/16” diameter 7050 rivets to larger suspended units capable of upsetting 3/8” diameter index head rivets in a single shot.

Automated LVER Assembly

Robots provide the flexibility to do assembly on many complex geometries but are relatively limited in payload, size and weight. Due to its lightweight and low recoil the mounting structure necessary for the LVER is significantly less than that from conventional hydraulic squeeze presses. The LVER drill/insert/rivet (DRID) end effecter weighs a mere 25 lbs and has a recoil force of under 75 lbs when upsetting 3/16” diameter rivets. This opens up new avenues for the assembly of complex structures such as wings and body panels since the tool can be easily moved past the part rather than the conventional cumbersome method of moving the part through the tool.

All mounted LVER actuators use a spring damper recoil system which can be easily adapted for use on any mounting structure, When the gun fires the driver moves forward into the work piece through a bearing located on the nose of the end effecter. The driver moves independently and is coupled to the remainder of the unit only through the electromagnetic force. By conservation of momentum, the gun body moves backward. Recoil transport is accomplished using a tube bearing system in which the gun body moves within a stationary outer shell. This outer shell is mounted directly to the robot or positioner. The gun body is brought to a stop by air springs over a distance determined by the mounting configuration. A hydraulic clamper is used to bring the gun body slowly back to the zero position to prevent possible skin damage. The longer the distance the recoil mass is allowed to travel the lower the peak recoil force felt by the mounting structure. In most cases 1” to 3” of recoil distance is sufficient to maintain the peak recoil force within a tolerable range as illustrated in Fig 2.

The LVER drill/insert/rivet (DRID) end effecter utilizes the innovative concept of concentric drilling. The concentric drilling technology allows all operations to take place under a continuous clamp-up without the use of a large shuttle system or tool changer. In this technology the coil, driver plate and driver are hollow allowing the drill motor to move down the center of the unit. Since the force between the coil and driver is dependent primarily upon the contact area and the gap width between using an annular coil and driver system does not compromise the force generation mechanism. The upset die is located on the nose of the machine and is shuttled into and out of position using a small air cylinder. Flathead rivets and slug rivets in countersunk hole are blown directly into the hole by means of a tube which swings into position. This is a simple and reliable method since the countersink helps to guide the rivet into the correct orientation. Insertion of rivets into non-countersunk holes requires a slightly different means of insertion such as rivet grippers or vacuum transfer. Plate 1 shows a photo of the DRID actuator that was developed for Alcoa.

On the buck side a conventional LVER actuator is used. Plate 2 is a photo and Fig. 3 is an explosion drawing of the LVER buck side riveter. These units are designed to form up to a ¼” diameter rivets. In operation, the driver is retracted to accommodate the drill and feeding operations. It is then advanced to bring the upset die in contact with the inserted rivet. Advancement and retraction is performed using the air springs which are also used to absorb the recoil. The rivet head is seated by setting the pressure on the head side springs slightly higher than those on the tail side. For slug rivets the protrusion height is set by advancing the buck side gun body against a hardstop located on the stationary outer shell. By setting a higher spring pressure on the buck side gun the rivet protrusion is properly set.

The drill motor currently used in the DRID is a 1 hp air motor which provides adequate torque for drilling ¼” countersunk holes. The air motor is diametrically small and lightweight making it a natural choice for use with the DRID. Axial feed of the drill and motor is performed by a constant speed pneumatic cylinder-hydraulic damper combination. Larger air or electric drill motors can be accommodated in the concentric configuration. Countersink depth is controlled using a hard stop and microswitch.

Cycle rate is always a critical issue when specifying an automated fastening system. The current high cycle rate DRID technology is capable of doing 10-15 rivets a minute. When the LVER is run at a high cycle rate resistance losses in the coil cause its temperature to rise. Heat is also transferred to the driver. Cooling must be provided to maintain the coil at a safe operating temperature. All high cycle rate LVER coils are radially drilled to allow cooling air to flow continuously through the windings while the machine is operating. After passing through the coil the air flows forward through a series of holes in the driver plate and out exhaust ports on the front of the gun body. Compressed shop air can be used provided it is clean and dry.

The lightweight and low recoil of the LVER DRID makes it ideally suited for use with a robotic positioner. If a flat die is employed on the buck side a relatively large amount of alignment error can be tolerated. But flat dies do not provide rivet interference as accurate alignment is required. It has been proposed to use the LVER system on two opposing robots. Precise alignment with two robots will be a challenge and may require special sensors and feedback loops. To resolve this difficulty Electroimpact has proposed traveling yoke systems. The yoke travels on ways attached to a floor assembly jig (FAJ). In the proposed system the part is assembled on the FAJ and is not removed until all riveting is completed. This saves considerable handling time and greatly simplifies the production process.

Since the LVER is extremely lightweight the yoke need only to be designed with adequate structure to provide the necessary clamp-up force, typically about 4% of the riveting force. The yoke is light enough to travel across the top of the FAJ. Fig 4 shows a three-axis traveling yoke concept which might be employed for spars or other flat parts. The yoke travels on a set of ways fixed on one side of the FAJ. One drive transports the entire yoke up and down (Z-axis) while a second drive transports the yoke along the long axis of the FAJ (X-axis). A third drive brings the drill side pressure foot bushing in contact with the panel (Y). The Y drive can be controlled by a non-contact eddy current sensor. One pressure foot bushing is servoed in contact with the part, subsequently the opposite side is driven into the panel by air cylinder to provide the proper clamp-up force. The three axis yoke is suitable for parts which have all rivets perpendicular to the axis of the FAJ such as spars. A five axis yoke is illustrated in Fig. 5. This system is designed to follow the complex contour of a fuselage or wing. Note that the fourth and fifth axes are relatively straightforward to implement due to the light weight of the traveling yoke. Several aerospace companies are currently considering the use of these traveling yoke systems.

Handheld LVER Riveting

The LVER has also been adapted into a portable handheld electromagnetic riveter (HHER). Two sizes of HHER are shown in Plates 3 and 4. An explosion drawing of an HHER actuator is shown in Fig. 6. Two opposing handheld actuators are connected to independent capacitor banks and a common control box. The actuators can be connected to the capacitor banks with a 20 ft cable while the control box is connected to the capacitor banks by a light gauge cable of any desired length. This allows the operators to work on opposing sides of large assembly panes as is common in many aerospace applications. An LED located on the gun body is activated by the trigger of the opposing gun and serves as a communication device between the two operators. The guns will not fire until both of the gun triggers are pressed. A second LED is used to indicate the status of the capacitor banks in reference to the specified charge voltage.

A number of safety features have been incorporated into the HHER. The HHER is entirely encased in a high strength non-conducting nylon body. This ensures that the operator is completely electrically isolated at all times. The electrical system is equipped with a sensitive ground fault detector and interrupt. Should a ground fault occur in the gun, cable or capacitor bank the system will automatically shut down and dump all charge from the capacitors. A spring is used to open up the gap between the driver and the coil when he driver is not in contact with the work piece. If the driver is held away from the coil dumping the capacitor bank creates negligible force. When the gun is to be fired the operator must compress this spring and bring the driver in contact with the coil. This insures that no damage will occur if the unit is accidentally fired.

The HHER has been designed with an internal recoil system. As shown in Fig. 6, the coil is directly attached to a steel slug, which is backed up by shock absorbing foam. When the gun fires the coil moves backward compressing this foam. This brings the mass to a stop over a distance, thereby reducing the peak force felt by the operator. The larger the distance the lower the recoil force.

With pneumatic hammers the size of the rivet determines the size of the riveting gun. This correlation also holds with the HHER. The larger the coil area and the larger the recoil mass the greater the amount of force which can be delivered to the rivet. For a given actuator the riveting force can be arbitrarily adjusted downward by reducing the voltage but the maximum force is limited actuator capability. For 3/16" diameter rivets a recoil mass of between 3 and 4 lbs is adequate. This results in guns that weigh about 8 lbs. as shown in Plate 3. This is still light enough for simple handheld operation. For ¼" diameter rivets the optimum gun weight is around 14 lbs as shown in Plate 4. Larger units have been constructed which are capable of forming 3/8" diameter 7050 index head rivets in a single shot. With counterbalancing these 150lb guns are comfortable to operate. The 3/8" diameter 7050 rivet is extremely difficult and time consuming to form with pneumatic hammers whereas the HHER performs this function in a single shot.

Since the firing signal is electrically synchronized the HHER is capable of installing slug rivets. Conventional handheld pneumatic rivet guns are not able to perform this function since they are driven from one side only. The protrusion height of the slug rivet is set using an adjustable collar on the nose of one of the guns as shown in Plate 4. The rivet is upset in one shot. Since the forces are equal and opposite negligible force is transferred to the panel.

Titanium interference bolts are being used more extensively in aerospace due to their increased strength. Larger diameter and longer grip length bolts are increasingly being employed. As a result, these bots are more difficult to install. Often times the bolt gets stuck in the hole as it is being installed. The only option at this point is to position the part in a large C-frame squeezer or drill the bolt out, both of which are slow processes. In the pin driving application a single gun is employed with a bucking bar on the opposing side. British Aerospace is currently testing the HHER for use in this application. For example 9/16" diameter bolts with .005" interference are easily seated in two shots.

One desirable feature of the HHER is that it is quiet in operation. The piercing sound of the pneumatic riveting gun is common to all aerospace assembly plants. The HHER operates at noise levels far below those of pneumatic tools. This is due to the lack of repetition and absence of pneumatic pressure release. The HHER is particularly quiet since it operates in the low audio frequency band. For example, an operator can comfortably stand next to an LVER and form a 5/16" 7050 rivet without hearing protection. This creates a more pleasant and safer working environment.

Rivet Quality

A riveting process is evaluated by the quality of the riveted joint which is produced. The term rivet quality encompasses tensile strength, shear strength, rivet microstructure and hole interference. These parameters relate to the riveted joint's corrosion resistance and fatigue life. Fatigue life is an especially critical parameter in light of the aging of current aircraft fleets.

Aircraft structures are subjected to a complicated series of varying loads and therefore fatigue. Holes in these structures are sites of severe stress concentration. A study of the appearance of fatigue failures shows that most failures originate at fastener holes [5]. Solid rivets are used to fasten aircraft parts together by filling these holes with a formed rivet. Acceptable rivet installation results in interference between the rivet and the hole. Interference is defined as the degree to which the upset rivet diameter is greater than the original hole diameter. Acceptable rivet interference values are typically between .002" and .012". This interference creates residual compressive stresses in the metal surrounding the hole and shields the hole from cyclical tensile stresses. Therefore, interference or hole fill is one of the determining factors in improved fatigue life of the structure.

The rivet formation dynamics of electromagnetic riveting are significantly different from the dynamics involved in hydraulic and pneumatic systems. As a result, forming parameters are not the same as with conventional techniques. Each application requires careful study to obtain optimum results. Rivet die design is a critical parameter in the successful operation of the LVER process. Typically a flat die is used on the rivet buck side. Flat dies however not appropriate for use with the LVER. This is due to the increased strain rate of formation. If a flat die is used the rivet head will easily form to the desired diameter with less material being pushed into the hole than desired. This implies inadequate interference and lower fatigue life. Increase the force delivered to the rivet merely results in further formation of the rivet buck tail without improving hole fill. Using cupped dies alleviates this problem by containing the rivet and pushing material into the hole as it is formed. The result is a conical buck tail and significantly improved interference.

Until recently electromagnetic riveting has been used exclusively for slug and index head rivets. Electromagnetic riveting (EMR) systems were developed and have been used by the Boeing Company since the early seventies [1,2]. Boeing currently employs the EMR to install slug rivets in the assembly of the 767 wing spars. The operating principles of the Boeing EMR and the LVER systems are essentially the same with the significant difference that the older Boeing system operates at a much higher voltage, around 10 kVDC. In the case of nearly symmetric rivets there is a significant amount of formation on both sides of the rivet. Electromagnetic riveting is ideally suited to these applications since the rivet is hit from both sides simultaneously with equal and opposite forces. In fact, there is currently not other method of installing slug rivets by hand where the distance from the edge of the part is over a few inches.

Recently a number of aerospace companies have expressed interest in using LVER systems for the installation asymmetric rivets such as flat and protruding head. The compliance on the buck side of these rivets is considerably greater than on the head side. As a result, the center of force is not in the center of the substrate. If equal simultaneous forces are applied, an excess force results on the head side which is resolved into the part. Conventional hydraulic squeeze systems overcome this problem by allowing the part to move slightly to compensate for the head deformation.

It is usually not desirable to rely on compliance in the part or its movement to compensate for the unsymmetrical rivet shape. Instead, the LVER overcomes this problem by electronically balancing the force. Force balancing significantly improves the rivet fatigue strength and results in a much more efficient upset since all of the energy is put into the rivet deformation. Further, it allows the part to remain stationary under rigid clamp up throughout the installation process. The amount of balancing required varies with the installation. Fig. 7 shows fatigue life versus force balancing bias for a Briles 7050 flathead rivet in 2024-T3 substrate. The fatigue life is increased nearly fourfold with balancing.

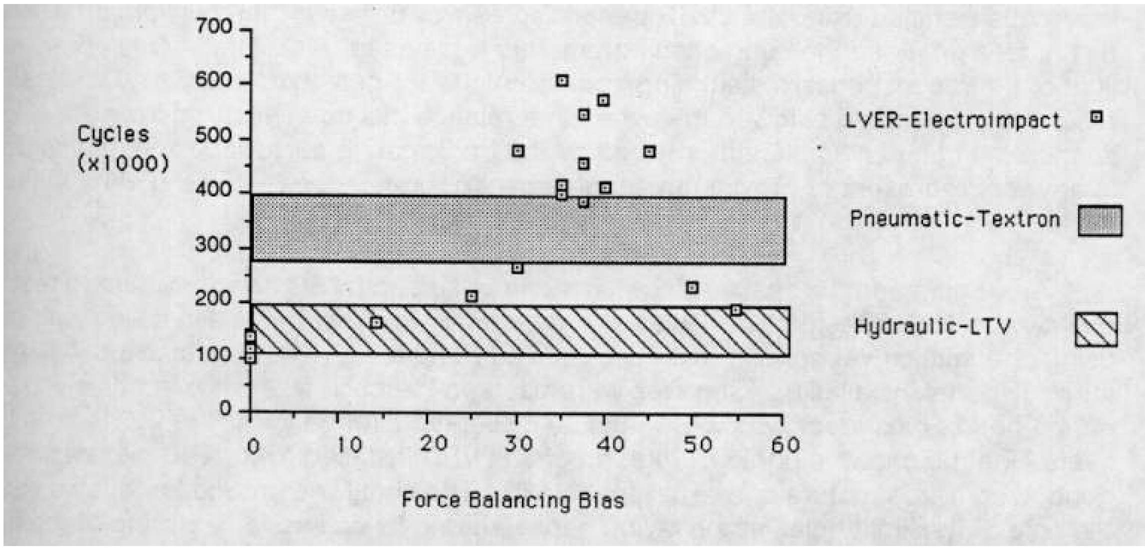

Figure 7: Effect of Force Balancing Bias on fatigue life for 7050 fatigue life for 7050 Briles countersunk rivets in .142” stack up. Test run at 24 ksi maximum stress with a .05 load ratio.

Aerospace companies have been concerned with the certification of rivets formed with the LVER process. Below are listed the companies which have generated programs for the evaluation or use of LVER technology.

Northrop:	Purchase of test bench for certification and for adaptation to drill/insert/rivet system. Purchase of small handheld for testing.
Boeing-Renton:	Purchase of test bench system for certification. Purchase of riveting head as part of drill/insert/rivet robot end effecter development.
Boeing-Wichita:	Purchase of large handheld system for the installation of 3/8” 7050 index head rivets on the 747 wing box.
Alcoa:	Purchase of concentric drill/insert/rivet robot end effecter for testing.
Lockheed:	Purchase of robot end effecter for certification.
Textron:	Purchase of two medium sized handheld systems for certification.
Douglas-Huntington Beach:	Lease of small handheld for testing.
LTV:	Purchase of concentric drill/insert/rivet robot end effecter for testing.
British Aerospace Hatfield:	Lease of robot end effecter for testing.
Chester:	Purchase of handheld development system for testing.
Avionsmarcel-Dassault:	Lease of robot end effecter for testing.

Note that most of the above systems have been purchased or leased for testing although several will shortly be in production. In nearly all cases these studies have found that rivets installed using the LVER performed as well or better than conventional techniques provided the suggested parameters were used. This is particularly relevant in light of the recent concern stemming form the Aloha airlines accident. Some of these results are presented below to the extent that release has been secured from the sponsoring companies. Data provided by the participating aerospace companies does not in any way represent or provide an endorsement or preference for the LVER by these companies:

A. Lockheed Aeronautical Systems purchased an LVER bench system to test rivet quality. Lockheed tested both Briles and proprietary Lockheed rivets installed with sealant using pneumatic rivet guns, a hydraulic squeezer and the LVER. The stack up was typical for body panel installation. Cup dies were used on the buck side while flat dies were used on the head. Flushness was well within the acceptable range for all the LVER installed rivets. Plate 5 shows a photomicrograph of an LVER installed rivet. This picture shows good rivet microstructure and excellent hole fill. This small line around the rivet is sealant in the hole. The slight holes at the faying gap were due to excessive deburring of the hole prior to installation.

Installation using the LVER with no balancing showed that the rivet fatigue lives were comparable to those of the conventional methods, slightly higher with the Briles rivets and slightly lower with the proprietary Lockheed rivet. When however the rivets were the LVER rivets were hit a second and third time with the LVER the fatigue life dramatically improved to over five times the results of conventional methods. These results indicate that a multiple hit LVER system might be indicated for highly fatigue critical structures. This would add about 1-2 seconds to the overall cycle time. Results of the samples using the force balancing were not available at the time of printing although the graph above shows that there should be a significant improvement with its use. In conjunction with this study Electroimpact installed and tested identical coupons with slug rivets installed in the place of flushheads. The geometric mean of these results was over 1.7 million cycles, comparable to the multiple hit results.

Sponsoring Company: Lockheed Aeronautical Systems

Specified Rivet: Briles MS 14218E6 3/16”. Diameter, -6 length
Lockheed LS 15905E6 3/16”. Diameter, -6 length

Coupon: Mil –Std- 1312 Method 21 Lap Shear (See Plate 8)
7075-T6 Aluminum, .160” stack (2-.080” plates)

Stress Level: 11 ksi maximum, .10 Load Ratio

Conditions: Installed with sealant
4 to 5 replicates of each installation were performed.

Installation Method Briles MS14218E6 in 7075-T6 Plate

	Pneumatic Rivet Gun	Hydraulic Squeeze	LVER (unbalanced)	LVER (triple hit, unbalanced)
Fatigue Life (x1000) Geometric Mean	175	271	285	1,667

Installation Method Lockheed LS15905E6 in 7075-T6 Plate

	Pneumatic Rivet Gun	Hydraulic Squeeze	LVER (unbalanced)	LVER (triple hit, unbalanced)
Fatigue Life (x1000) Geometric Mean	296	381	269	1,944*

*One coupon was removed at 2.4 million cycles with no failure.

B. Textron Aerostructures purchased two medium size handheld units for rivet quality studies. These units are being used to install 316” and ¼” diameter 2117 aluminum slug rivets into countersunk holes in 7150 plate. The anticipated application is for attaching wing skins to spars in the Airbus A330. In this application one actuator is outfitted with an adjustable collar on the nose. Plate 4 shows the gun with the cage used to set the rivet protrusion height. The distance between the end of the cage and the bottom of the rivet die determines the protrusion height. Offset tooling was also supplied to enable installation of rivets hidden behind upstanding stringer legs.

A number of tests were performed to determine the operating voltages which produce interferences in the middle of the .002” - .012” specification. The force balancing bias is not used in this application since the rivet is relatively symmetric. The results indicate that the amount of interference is directly related to the discharge voltage. This is expected since the discharge voltage determines the applied force. Die design was also found to be a critical parameter in determining interference. Pyramid shaped cup dies were used on the buck side and shallow concave cup dies were used on the head. These two dies help to contain the rivet and drive material into the hole as it is formed.

Sponsoring Company:	Textron Aerostructures
Specified Rivet:	2117 slug rivets, 3/16” and ¼” diameter 7075-T6 Aluminum (Plate 9) .375 Stack up for 3/16” rivets 1.032 Stack up for ¼” rivets
Conditions:	Installed without sealant
Other:	Rivets were installed using handheld electromagnetic riveters. Interference tests were performed using voltages determined to give interference on the low side of the specification to simulate a worst-case situation.

Fig. 8 illustrates that the interference values for the ¼” rivets in 1.032” stack up are fairly uniform through the hole and are repeatable from rivet to rivet. The interference near the buck side and near the countersink are slightly higher as can be observed with the hydraulic squeeze process. It should be noted that even though the discharge voltages were set slightly low and these rivets were installed by hand none of the interferences fell out of the specified range. Fig. 9 further demonstrates the repeatability of the LVER process. Fifty 3/16” diameter rivets were installed by HHER with several different operators. Interferences were measured at the indicated locations. Again, even though the voltages were set slightly to the low side of the determined range none of these rivets fell out of specification.

Textron is also performing a series of fatigue tests to aid in qualifying the electromagnetic process. Some preliminary tests have shown favorable results. The interference values indicate that acceptable fatigue life should be anticipated. No results are presented here since the tests are still in process at this time of writing.

C. Early in LVER development one aerospace company was interested in using the system for the installation of body panel rivets. Fatigue results were disappointing though when compared with conventional methods. Tests however were not representative of the current technology since the rivets were installed using flat dies on the buck tail without force balancing.

Electroimpact then began a study of rivet quality for the body panel application. A number of coupons were installed and tested to determine the appropriate operating parameters. The LVER rivets were installed at Electroimpact with a bench top unit similar to the one employed by Lockheed (Plate 6). Identical coupons were sent to Textron Aerostructures for installation of rivets using a pneumatic rivet gun and bucking bar. Coupons were also sent to LTV for installation using a conventional hydraulic squeeze press. All coupons were tested to failure using the Electroimpact MTS fatigue squeeze shown in Plate 7. The results illustrate a marked increase in fatigue life when using the LVER with cup dies and force balancing. Multiple hits using the LVER did not increase the fatigue life as with the Lockheed tests. This was probably due to the softer 2024-T3 coupon material and resulting excessive interference.

Specified Rivet: Briles MS 14218E6 3/16". Diameter, -6 length

Coupon: Non-Load Transfer Dogbone (See plate 10)
2024-T3 Aluminum, .142" stack (2-.071" plates)

Stress Level: 24 ksi maximum, .05 Load Ratio

Conditions: Installed without sealant

Other: Tests were performed by Electroimpact.

Installation Method Briles MS 14218E6 in 2024-T3 Plate

	Pneumatic Rivet Gun	Hydraulic* Squeeze	LVER no balancing flat dies	LVER With balancing
Fatigue Life (x1000)	321	194	133	459
	332	121	144	611
	294	146	194	579
	391	221	119	458
	284	163	121	549
	262	170	205	402
Geometric Mean	311	166	149	504

*Coupons were drilled/inserted and upset with an automatic riveting machine.

CONCLUSION

The above case studies illustrate that good rivet quality is attainable with the LVER process provided correct operating parameters are employed. These parameters are specific to the envisioned application and need to be experimentally optimized through a series of tests. Correct die design and system settings are critical for acceptable performance. Electroimpact welcomes requests from aerospace companies to perform interference and fatigue tests that will aid in determining the optimum parameters for use of LVER in specific applications.

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APPENDIX

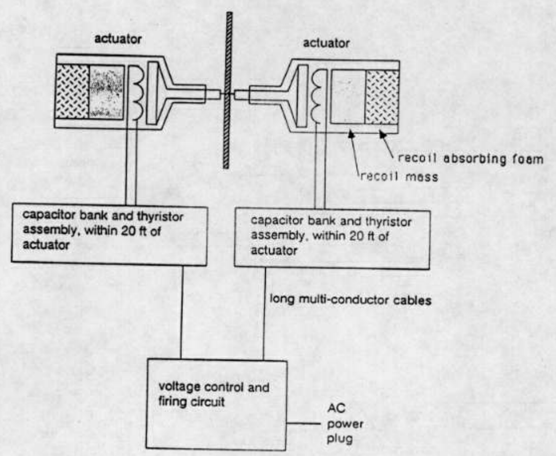


Figure 1: LVER Block Diagram

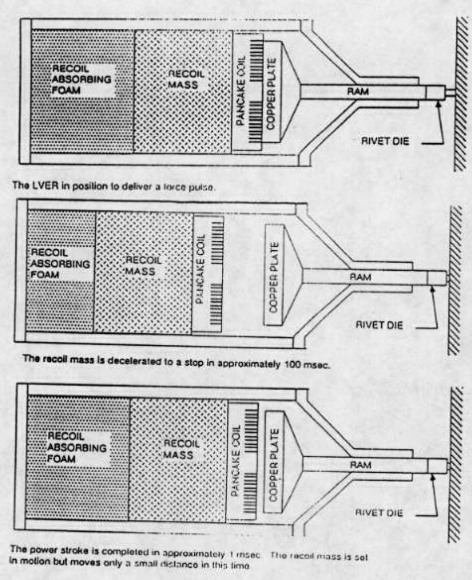
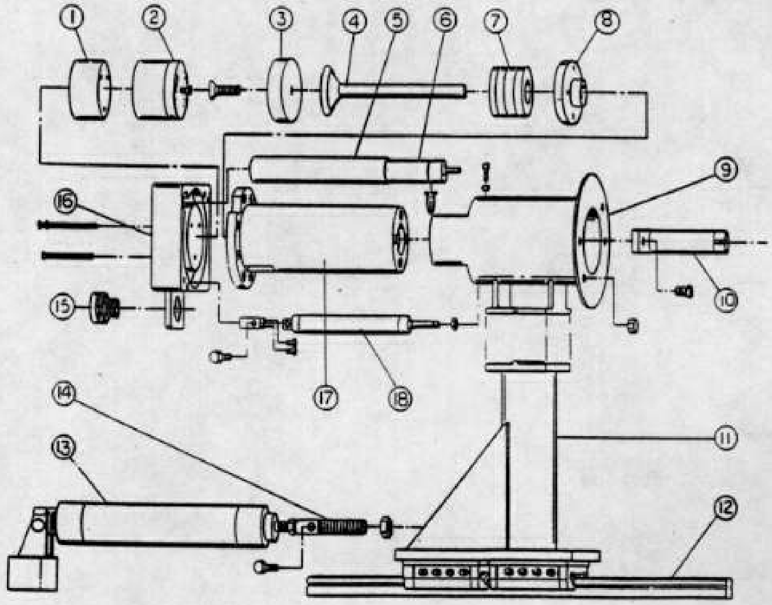


Figure 2: Operating Sequence of the LVER Recoil Control System



NO.	DESCRIPTION
1	PHENOLIC SPACER
2	COIL
3	DRIVER PLATE
4	DRIVER
5	DAMPER TUBE
6	DAMPER
7	BOUNCE PLATE
8	FRONT PLATE
9	S.S. BODY
10	CLAMPUP NOSEPIECE
11	TRANSPORT CART (OPTIONAL)
12	TRANSPORT RAIL (OPTIONAL)
13	AIR CYLINDER (OPTIONAL)
14	ADJUST. SCREW (OPTIONAL
15	CABLE CLAMP
16	BACK PLATE
17	NYLATRON BODY
18	RECOIL CYLINDER

Figure 3: Electroimpact Robot End Effector Riveter
Explosion Drawing

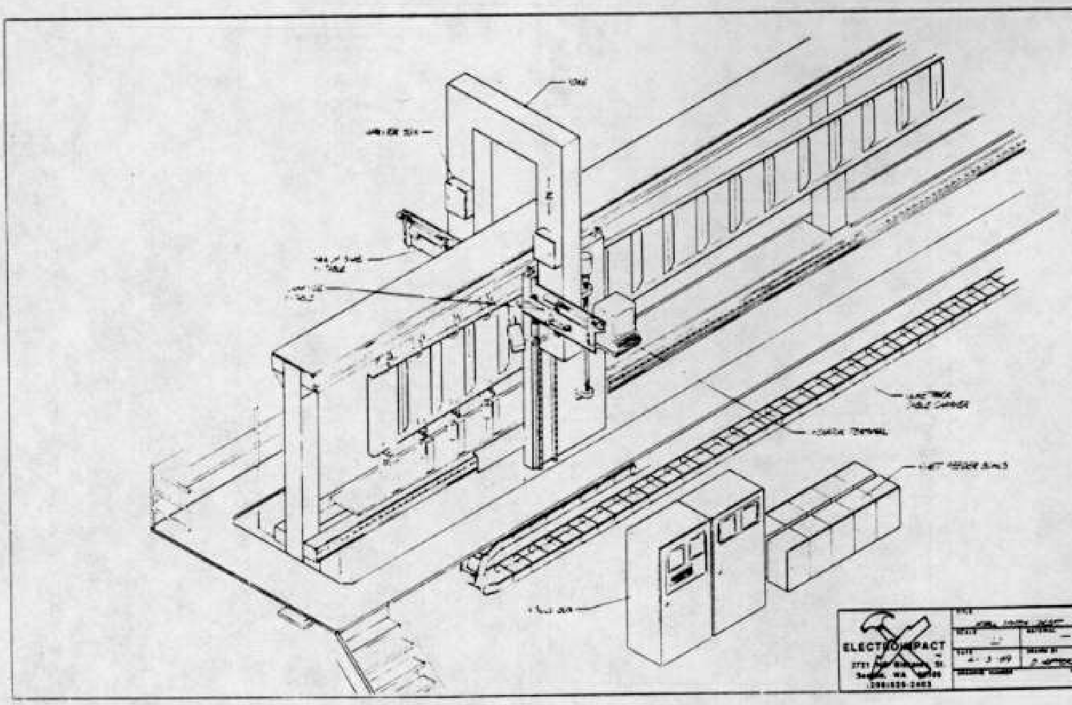


Figure 4: Proposed Three Axis Yoke System

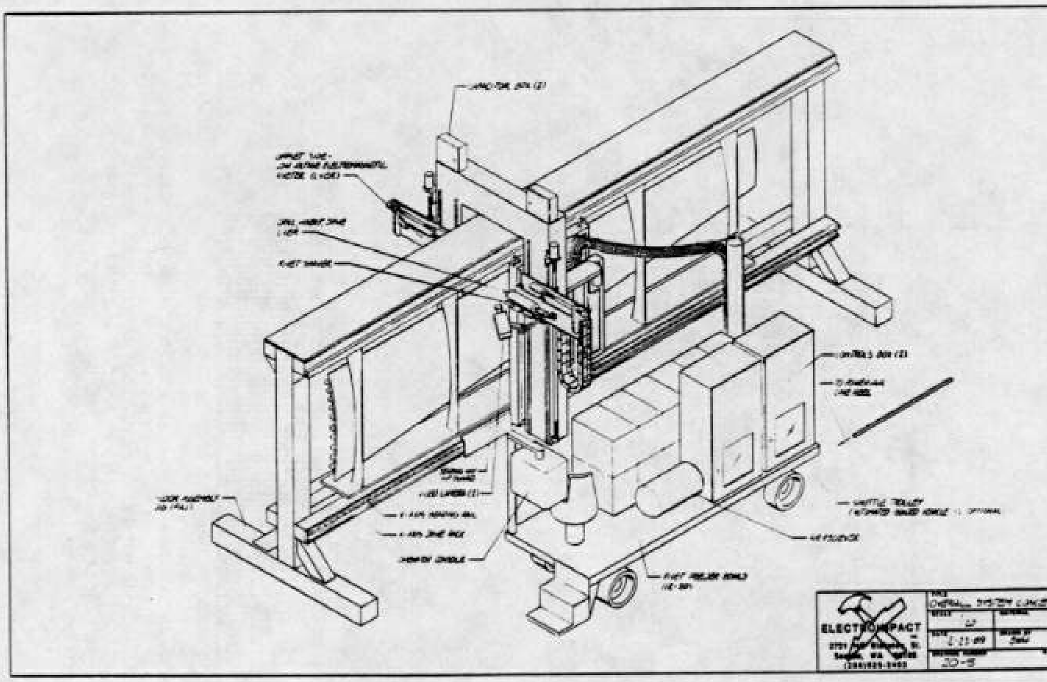
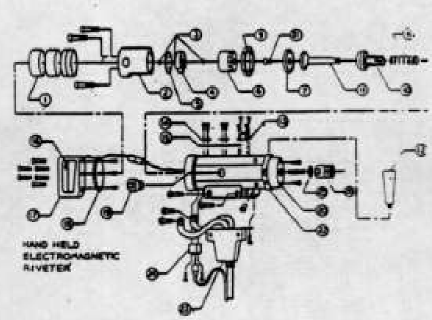
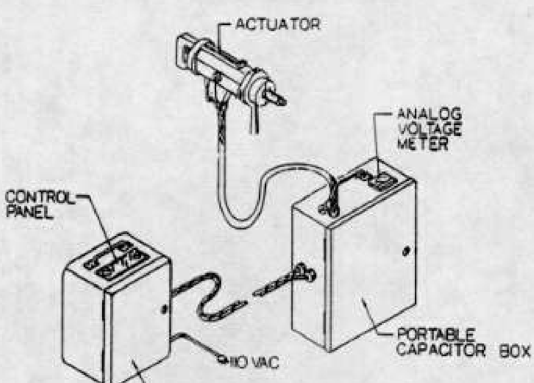


Figure 5: Proposed Five Axis Yoke System



PARTS LIST

1) Recoil Absorbing Foam (Densities, XH,H and M)
2) Recoil Mass
3) Recoil Mass O-ring
4) Lead Spacer
5) Lead Separator
6) Coil
7) Driver Plate
8) Pop-out Spring
9) Driver Stop Ring
10) Front Bearing Plate
11) Driver
12) Auxiliary Support Handle
13) LED Housing
14) LED Cable Cover Tie Down
15) LED Cable Cover
16) Trigger
17) Handle
18) Backplate
19) Cooling Port Adapter
20) Driver Grounding Wire
21) Driver Plate Retaining Bolt
22) Gun Body
23) Cable Housing
24) Control Cable Support



CAPACITOR BOX AND CONTROL BOX SCHEMATIC

Figure 6: Electroimpact Handheld Electromagnetic Riveter
Explosion and Overall System Drawing

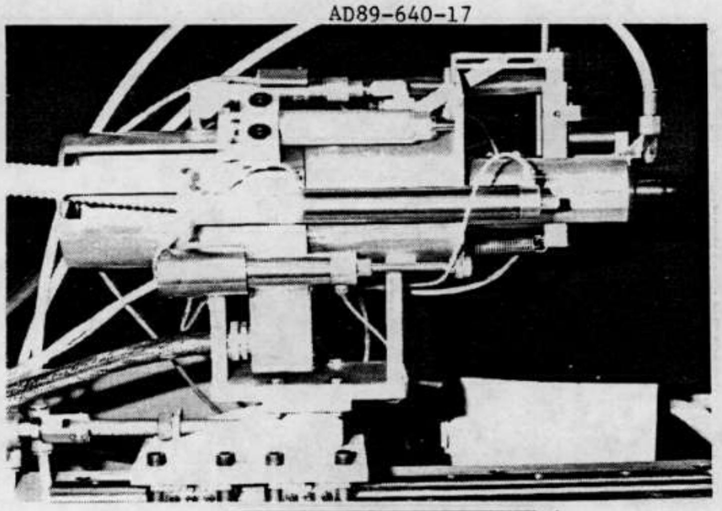
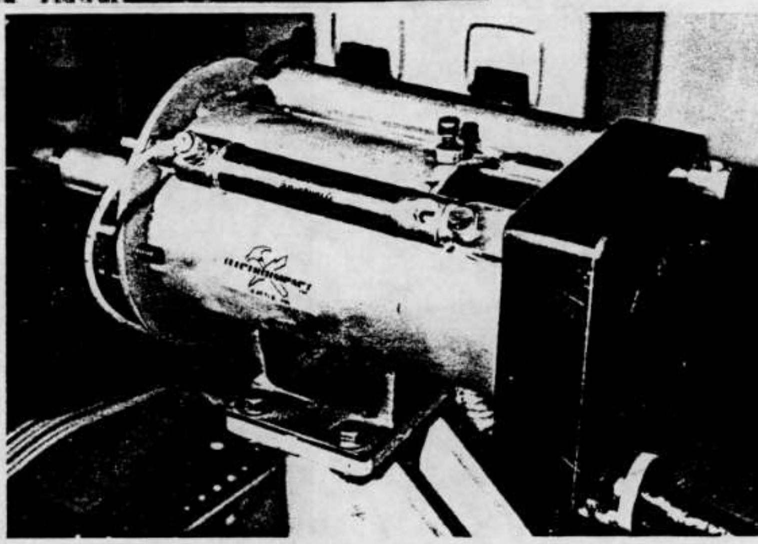


Plate 1:

LVER-Drill/Insert/Drive End Effector

Plate 2:

LVER-End Effector Rivetor



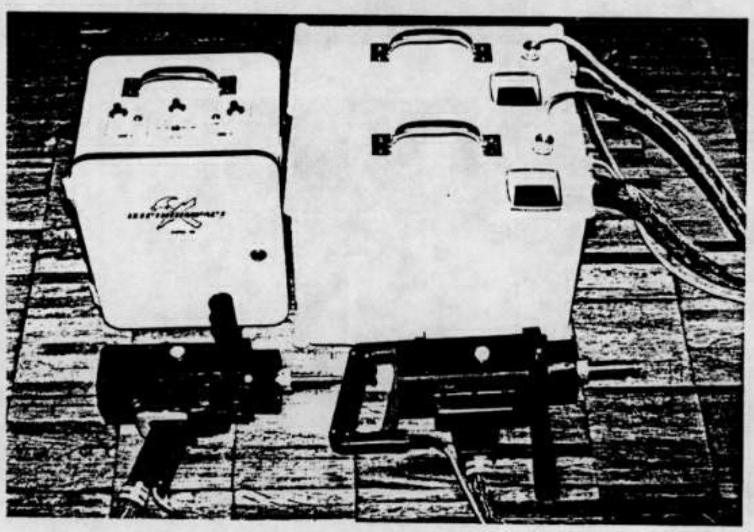


Plate3:

Small HHER System

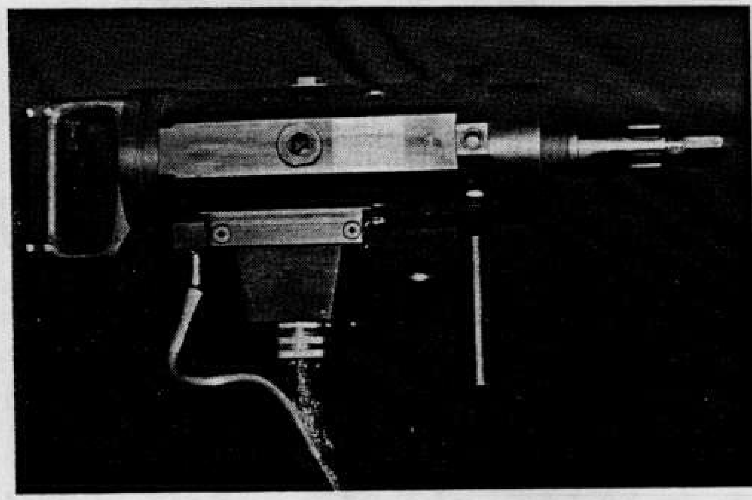
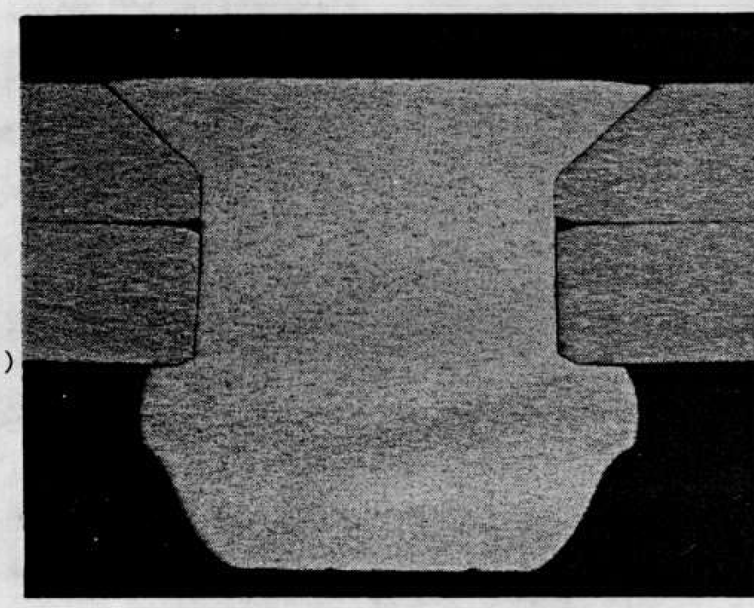


Plate 4:

Medium Size
HHER Actuator

Plate 5:

Photomicrograph 3/16"
Diameter Rivet
(Courtesy of Lockheed
Aeronautical Systems Co.)



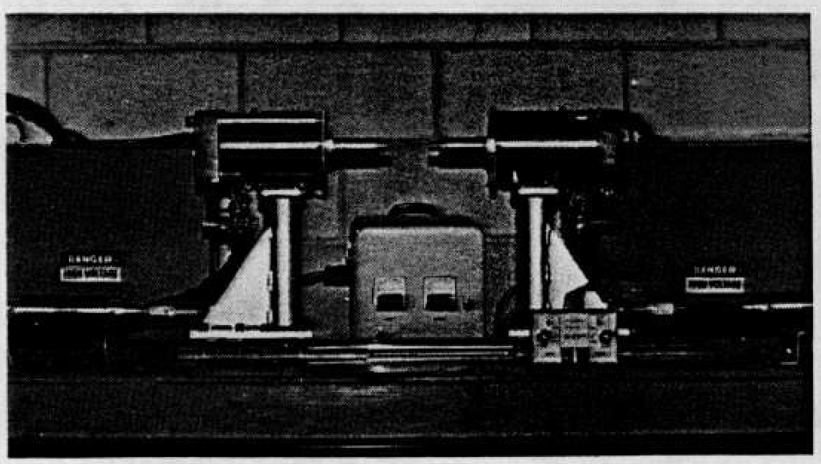


Plate 6:

LVER Bench Top
Riveter

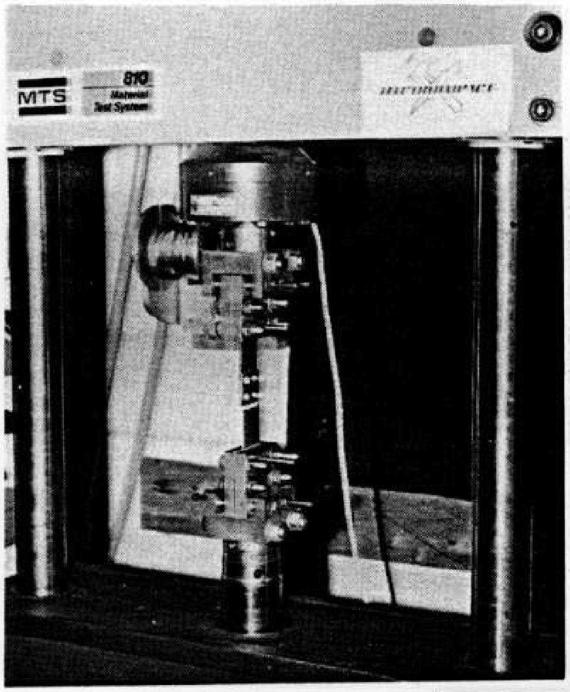
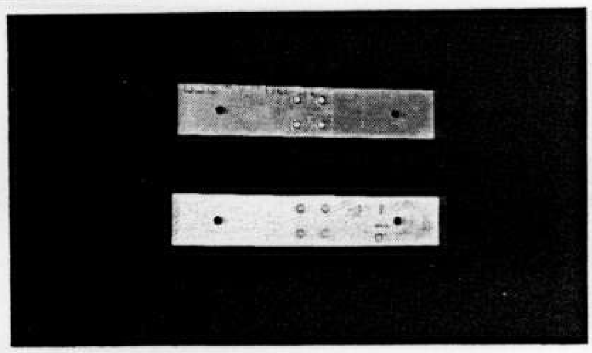


Plate 7:

Electroimpact MTS
Fatigue Testing
Machine

Plate 8:

Lap Shear Fatigue
Coupons. 7050 3/16" Diameter
Flathead Rivets in 7075 Plate



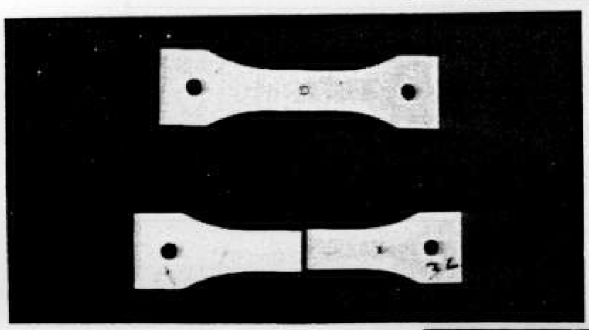


Plate 9:

Lap Shear Fatigue
Coupons. 2117 3/16"
Diameter Slug Rivets
in 7075 Plate

Plate 10:

Non-Load Transfer Fatigue
Coupons. 7050 3/16" Diameter
Flathead Rivets in 2024 Plate