

Low Voltage Electromagnetic Riveter

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ABSTRACT

The low voltage electromagnetic riveter (LVER) differs from previous models of electromagnetic eddy current driven riveters (EECDR). It employs low voltage electrolytic capacitors and thyristors. The LVER operates at 500 VDC maximum in comparison with the 10 k VDC typical of the existing EECDR technology, and is relatively safe, compact and inexpensive. Despite the low voltage, a small LVER is capable of generating a peak force of 90kNt, more than adequate for one shot upset of a 3/8" diameter 7050 rivet. Due to the low voltage, the LVER provides a force risetime much slower than the high-voltage system. This slower risetime is quite advantageous for the formation of strain rate sensitive materials such as 7050.

INTRODUCTION

Electromagnetic eddy current driven riveting (EECDR) is a technique employed by at least two aerospace manufacturers. A narrow force pulse is generated, thereby minimizing the recoil transmitted to positioning equipment. The electromagnetic riveter therefore can be positioned by lightweight mechanized equipment, and even hand held. Opposing devices can be electrically synchronized, thus permitting the upset of large diameter rivets without throat depth limitations. The use of equal and opposing forces permits the installation of slug rivets without transmitting force to the adjacent structure.

An advantage of the EECDR is that the primary operator function is to preposition the actuators. With the actuators properly positioned the output force pulse is quite predictable, and in one "shot" the rivet is fully formed. Therefore an unskilled operator, or even a machine, can reliably form rivets. The operator has very little opportunity to cause skin damage.

The low voltage electromagnetic riveter (LVER) proposed by Electroimpact, Inc. is a design of EECDR which operates at a relatively low voltage. The LVER operates with a maximum capacitor bank voltage of 500 VDC in contrast to the 10 kVDC typical of other designs. Despite the low voltage a compact LVER routinely can generate a force pulse of 90 kNt peak, adequate for the one shot upset of a 3/8" diameter rivet. There are numerous advantages of the LVER in comparison to the existing high voltage technology: low cost, safety, small size, flexibility, and a superior pulse shape. These advantages are discussed below in further detail.

RIVETING TECHNOLOGIES

There are at least three means of upsetting solid rivets: by pneumatic impact, hydraulic squeeze and one-shot electromagnetic eddy current driven riveter (EECDR). Most rivets are installed by the hand held pneumatic impact riveting gun. The piercing noise from the device is a distinctive feature of aerospace assembly plants. The loud noise is primarily on the "buck" side, as the bar is thrown off the plate against its own momentum and the pressure of the operator. As illustrated in Fig. 1 a preheaded rivet is required in pneumatic riveting; the forces are inherently uneven, and thus the head is required to locate the rivet. To provide for at least some plastic flow on the preheaded side one rivet design adds a crown to the top of the rivet head (2-5). In any case the resulting hole interference from a preheaded rivet is much greater adjacent to the buck side than to the head side.

In pneumatic hand riveting multiple blows are employed. A hand riveter with sufficient power to form a rivet in one shot was developed (6-7), but never gained wide acceptance due to problems with rivet quality. Some of these quality problems were the result of the fast risetime force pulse inherent to a low mass mechanical impact system.

Both hydraulic squeeze and EECDR provide balanced forming pressure and therefore are capable of installing preheaded as well as slug rivets. The primary advantage of the slug rivet is that a significant amount of plastic flow occurs on both ends of the rivet as illustrated in Fig. 2. An hourglass shaped interference pattern results, with a minimum of hole interference in the middle. Typically aerospace standards dictate that a rivet must interfere with the hole by at least .001". Rivet interference is measured by cutting the rivet from a test plate, as illustrated in Plate 1, and subtracting the initial hole diameter from the rivet body diameter. A properly installed rivet flows into, fills and stretches from the hole. Good interference enhances mechanical properties and also ensures that the joint is sealed against air and fuel leakage.

A hydraulic squeeze press reaches around the structure and squeezes the rivet from opposing sides. The bending moment that must be resisted is proportional therefore to the distance from the center to the edge of the plate. Thus hydraulic machines become large for fasteners located far from the edge of the structure. Because of their massive size, hydraulic squeezing machines often are unable to function in difficult to reach areas.

The EECDR generates adequate force to completely form a rivet in one shot. A narrow pulse width is formed, about 100 microseconds for high voltage designs and about 1 msec for the LVER. Since the force is of electrical origin opposing actuators can be fired synchronously to permit the use of slug rivets and the transmittance of only a minimal amount of differential force to the workplace.

The noise which results from use of the EECDR is considerably less than pneumatic riveting noise. This is due to the lack of repetition and the absence of pneumatic pressure release. The LVER is particularly quiet since it operates in the low audio frequencies. For example, an operator comfortably can stand next to an LVER and form a 5/16" diameter 7050 rivet without hearing protection.

If two pneumatic powered impact guns were positioned on opposing sides of a plate, even if simultaneously triggered, there would be an uncertainty in the transit time of the pistons down the cylinders due to uneven friction or other variables. Therefore simultaneously triggered opposing pneumatic actuators could result in a differential force, which could bend or otherwise damage the workpiece. The same problem would result from opposing mechanical hammers.

Due to the recoilless design there is no requirement for structure stretching around the workpiece with the LVER. Instead, since momentum is the time integral of force, the narrow pulse width permits the transfer of reaction force to the kinetic energy of a sliding recoil mass.

The eddy current mechanism of the EECDR is a unique electrical means of generating a large force with a fast risetime. In general a solenoid will not provide a fast force risetime; its force risetime is delayed due to the eddy current phenomenon. Whereas the force pulse will lag the current pulse in a solenoid, the force pulse will lead the current pulse in an eddy current device. The force density of the common solenoid is limited by the saturation characteristics of the iron core. The typical force density for several types of linear actuators is as follows:

Solenoid	160 Nt/cm ²
Pneumatic	70 Nt/cm ²
Hydraulic	3500 Nt/cm ²
EECDNR	2000 Nt/cm ²

Note that the high achievable force density of the EECDR allows the formation of large diameter rivets with a small actuator.

The operating sequence of the Electroimpact, Inc. recoil control system is illustrated in Fig. 3. Although a peak riveting force of 90 kNt (20,000 lbs) can be generated, reaction force is transferred to the support structure only through the air cylinder. A pressure relief valve limits the braking force of the air cylinder to a moderate value such as 530 Nt (120 lb).

The multiple blows required of pneumatic impact riveting allow for considerable variability in the process, and a well-trained riveter therefore is required. In comparison, the EECDR operator need only preposition to the device to properly form a rivet. Before discharging the capacitor banks the coil/driver/rivet/driver/coil system simply is brought into mechanical contact along their common axes. There are no recoil forces preceding the rivet upset as in the case of a mechanical impact system.

The prior art of electromagnetic eddy current driven riveting (EECDR) is represented by Wildi (8), numerous patents assigned to Boeing and Grumman (9-24), and others (25-26). The early patents on EECDR technology are expired or nearly expired. Later patents deal with specific components and configurations such as coils, power supplies and cables. The LVER is a significant departure from earlier designs and employs newly designed components throughout.

The EECDR system was developed as an outgrowth of the early work of Harvey on the magnetic forming of sheet metal (27). Harvey showed that conductive sheet metal could be formed by placing a workpiece in close proximity to a spiral wound pancake coil (as well as other configurations). By discharging a high voltage capacitor bank through the coil a rapidly rising magnetic flux is generated which induces eddy currents in the sheet metal and thereby creates a repulsive force for forming. These thin workpieces have a very short magnetic contact time, so to be effective in this application an extremely fast risetime is essential. Thus this system is characterized by high voltage, and cumbersome high voltage switching technology.

Wildi added a driver to this system to create a general purpose actuator. Since the driver is used over and over, the thickness and conductivity of the driver cladding can be adjusted at will. The restriction to use of high frequency to contact thin sheet metal no longer applies. Yet most EECDR systems still employ high frequency. In contrast the LVER operates at a frequency of just 350 Hz.

LOW VOLTAGE ELECTROMAGNETIC RIVETER DESCRIPTION

A block diagram of the dual LVER is shown in Fig. 4. Note that synchronization of the two actuators is achieved through trigger signals. This is in contrast to other EECDR designs, which employ series connection. The complexity and cost of a high voltage power supply and switching system make series connection attractive. Yet the large size of aerospace structures implies that the series connection may involve several hundred feet of high voltage cable. And since an EECDR typically requires an operating current pulse of over 10,000 ampere, the losses in such a long cable run are significant.

A design goal of the LVER is to keep the voltage low. Low voltage is desirable from many viewpoints including safety, cost, size, noise, etc. Charge storage therefore is local to the two guns, and connection is made through short low resistance cables of no more than 20 ft. Synchronization is achieved through simultaneous gate signals to the two output thyristors.

With respect to operator safety, many regions enforce special restrictions on the use of electrical equipment at voltages above 600. Therefore the 500 VDC max LVER is not subject to these regulations, a significant advantage to the user. All components of the LVER float with respect to the ground, further minimizing the hazard.

Since synchronization is achieved through gate signals, either of the two actuators can be fired independently for jobs such as driving rib bolts or setting collars. The energy of the two actuators can be adjusted independently in either of two ways. The local capacitor banks can be charged to different voltage. In addition, the capacitance of the two banks can be varied independently by adjusting the number of units attached to each bus.

The low voltage characteristic of the LVER permits the use of thyristors and electrolytic capacitors. For example, a thyristor capable of switching the 12,000 amp pulse required for forming a 5/16" diameter rivet is the size of, and is referred to as, a hockey puck. The cost of this device is several hundred dollars, and it is switched into a conducting mode with a simple trigger pulse. The electrolytic capacitors employed by the LVER are mass produced for electronic service. Because of this, as well as the simpler low voltage construction, electrolytic capacitors are relatively inexpensive. The energy density of electrolytic capacitors is extremely high in comparison to other capacitor technologies. These modern components allow the charge storage modules in the vicinity of the guns to be compact.

A logical extension of this approach under development by Electroimpact for small jobs is an actuator with charge storage within the gun body. This system, illustrated in Figure 5, would be inherently portable. The output capabilities of this device are not yet known.

In returning to Figure 4, it can be seen that a common power supply is employed for the two guns. This should be considered a cost measure, since independent supplies also can be utilized. Electroimpact employs a switch mode power supply design which is capable of bringing both banks to full charge within several seconds. Since each capacitor bank has a full charge of about 3.6 kJ, up to ten seconds will be required if only a regular 115 VAC outlet is available. Conventional 16 GA wiring of any length is appropriate between the power supply and the capacitor bank since only a modest charging current of about 4 A flows through these wires. A high current flows in the connection between the capacitor bank and the actuator, about 15,000 A. Therefore these latter leads must be kept short.

The low frequency characteristic of the LVER is particularly advantageous when forming a strain rate sensitive material such as 7050. If 7050 is formed too rapidly thermal feedback can lead to shear zone banding and even cracking. This problem is not observed when the LVER is employed. Plate 2 is a 50x photomicrograph of the shear band at the head inside corner of a 7050 rivet formed by the LVER. Plate 3 is a photomicrograph of the same location for a rivet formed in a hydraulic squeeze press. The slow forming speed of the hydraulic machine results in an extremely broad shear zone, whereas the LVER concentrates the shear band into a metallurgically acceptable flowline. Higher speed formation can further concentrate the flowline and cause irregularities in the microstructure.

Another advantage of the short leads is that the LVER coil becomes the dominant impedance of the system. The system impedance is altered dramatically by adjusting the coil dimensions and winding thickness, thereby altering the LVER operating frequency. LVER coils are composed of conductive ribbon wound in a spiral pancake configuration. For a given inside diameter, outside diameter and pancake depth, both the inductance and resistance of a coil will vary inversely to the square of the ribbon thickness.

LOW VOLTAGE ELECTROMAGNETIC RIVETER THEORY

An essential feature of the LVER is recoilless operation. The operating mechanism can be understood from Figs. 3 and 4. For the sake of illustration assume that a triangular force pulse of 90 kNt peak and 1 msec duration is generated. A total recoil momentum of 45 Ntsec is generated. If the braking force from the air cylinder is set to 530 Nt the recoil mass is decelerated to a stop in 85 msec. If a recoil mass of 15 kg is employed the equations of motion can be integrated to determine the total recoil distance:

$$x = \int_0^t a d\tau d\tau \quad 1$$

x = distance of recoil mass travel
 a = recoil mass acceleration
 t = time until recoil mass is decelerated to a stop

Newton's law is employed to substitute for the acceleration:

$$a = F/m \quad 2$$

Since both F and m are constant Eq. 1 can be easily integrated:

$$x = (F/m)1/2 t^2 \quad 3$$

Substitute the assumed values:

$$\begin{aligned}
 F &= 530 \text{ Nt} \\
 m &= 15 \text{ kg} \\
 t &= .085 \text{ sec}
 \end{aligned}$$

The recoil mass is therefore brought to a stop in 12.8 cm, or 5". The generated 90 kNt force pulse is adequate for the formation of a 3/8" diameter rivet.

The LVER is to good approximation a capacitor discharge system as illustrated in Fig. 6. The current waveform which results from a switch closure is the well known damped sinusoid. Of particular importance is the achievable value of peak current, which sets and upper limit on the achievable magnetic pressure. Due to low loop resistance a current pulse of 15,000 Ampere peak occurs in the LVER, with the peak occurring in about 750 microseconds.

The force generating mechanism in the LVER is the gap induction, illustrated in Fig. 7. In the absence of the passive copper driver plate the field lines from the coil would assume a doughnut like shape. But due to the shielding effect of this plate the field lines are squeezed together in the coil to driver gap. Initially the high induction in the gap will dominate the field pattern. Although field lines all must loop back onto themselves, outside of the gap they spread out rapidly and represent only negligible energy.

For the condition in which the gap field dominates the gap induction is simply equal to the surface current. Therefore for a circuit current of 10,000 Ampere and a coil turn density of 1000 turns/meter, the surface current and gap induction easily can be computed (28):

$$K = H = 10^7 \text{ Amps/m} \quad 4$$

K = surface current
 H = magnetic field strength

In the high frequency system Eq. 4 would be a good approximation. In the low voltage system only about half of this field remains in the gap due to magnetic diffusion.

The Maxwell stress tensor is the relationship between the gap induction and force (28). For a purely radial field a simple relationship results:

$$F = \frac{1}{2} \mu H^2 A \quad 5$$

F = total magnetic force

A = gap area

Transverse field lines such as those illustrated in Fig. 7 result in a positive force, or repulsion. The normal field lines typical of a solenoid result in negative force, or attraction.

The repulsion area of the LVER actuator is about 50 cm².

Substituting the above values into Eq. 5, including the lost field factor of 1/2, results in a total actuator force of 78.5 kNt.

The peak riveting force will deviate somewhat from this value due to the dynamics of the driver/rivet system. The force versus upset curve for four 5/16" diameter 7050 rivets is shown in Fig. 8. The rivet represents the bulk of the compliance of the rivet/driver mechanical system. From Fig. 8 an effective spring constant can be calculated as the ratio of the peak riveting force divided by the maximum rivet displacement:

$$k = F/x = 75 \text{ kNt}/.0033 \text{ m} = 2.27 \times 10^7 \text{ Nt/m} \quad 6$$

k = rivet spring constant

The mass of this same system, about 2 kg., is primarily in the driver. An effective natural frequency therefore can be calculated:

$$f = (\frac{1}{2} \pi) \text{ root}(k/m) \quad 7$$

f = rivet/driver effective natural frequency

The resulting natural frequency is about 512 Hz. The LVER's electrical pulse frequency is about 350 Hz. The electrical frequency will therefore determine the deformation rate since this is the slower of the two. But since the two frequencies are relatively close an oscillatory output results which enhances the peak riveting force.

The magnetic diffusion phenomenon determines the period in which field lines can be concentrated in the gap. Field lines diffuse through the passive copper driver plate because of its resistance. A magnetic diffusion time constant has been defined (28):

$$\tau = \mu \sigma d^2 / \pi^2 \quad 8$$

τ = magnetic diffusion time constant

$\mu = 4\pi \times 10^{-7} \text{ H/m}$ = free space permeability

$\sigma = 5.9 \times 10^7 \text{ mho/m}$ = copper conductivity

d = diffusion depth

An approximate depth for the penetration of magnetic flux can be calculated by substituting the time to the peak of the LVER current pulse, about 750 microseconds.

$$d = 10 \text{ mm}$$

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The diffusion depth is not insignificant and accounts for the approximate 50% reduction in gap field strength for the LVER. The relationship between current, time and gap field strength is complex but can be determined with sophisticated computer modeling. In the LVER the Copper driver plate (illustrated in Fig. 7) is relatively thick to compensate for the low frequency.

From Fig. 8 it can be seen that the energy of deformation to form a single button head of a 5/16" diameter 7050 rivet is about 120J. This is only about 3.3% of the electrical energy which must be stored in the LVER capacitor bank to form the head. The bulk of the energy is lost to electrical resistance. But calculations reveal that 3.3% efficiency is better than that achieved by the pneumatic impact gun.

CONCLUSION

The many positive features of the LVER make it an attractive alternative for use in aerospace riveting. A lease/demonstration system should be available shortly, with production units available sometime next year. The projected cost for a complete LVER riveting system is thirteen thousand dollars; greater than that of a pneumatic riveting gun, but justified by the quality, high productivity, precision and safety of the device.

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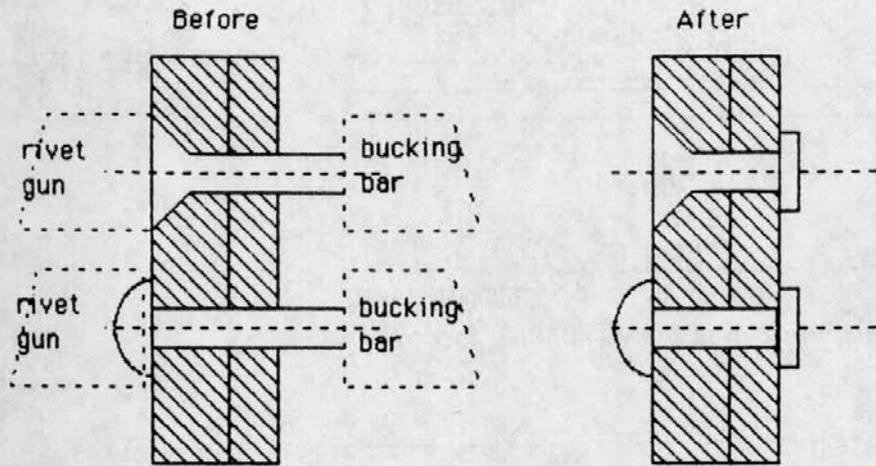


Figure 1 Flush and button head rivets installed by a pneumatic riveting gun. A preformed head is required to locate the rivet.

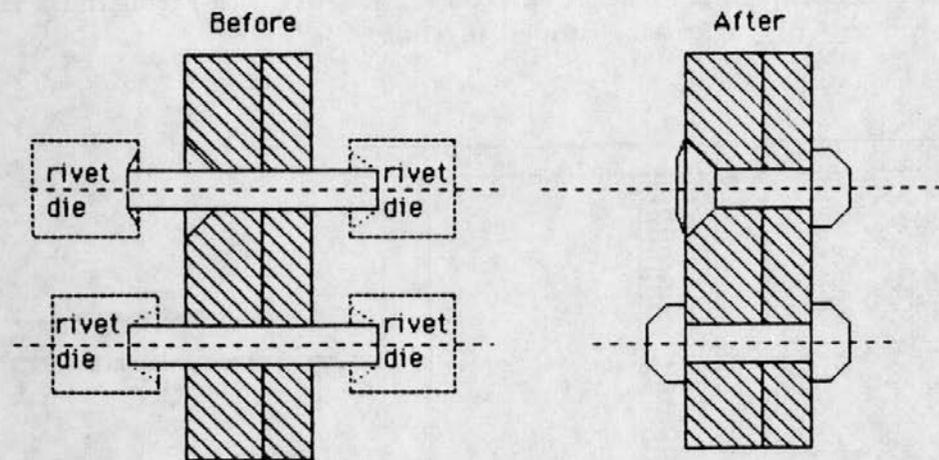
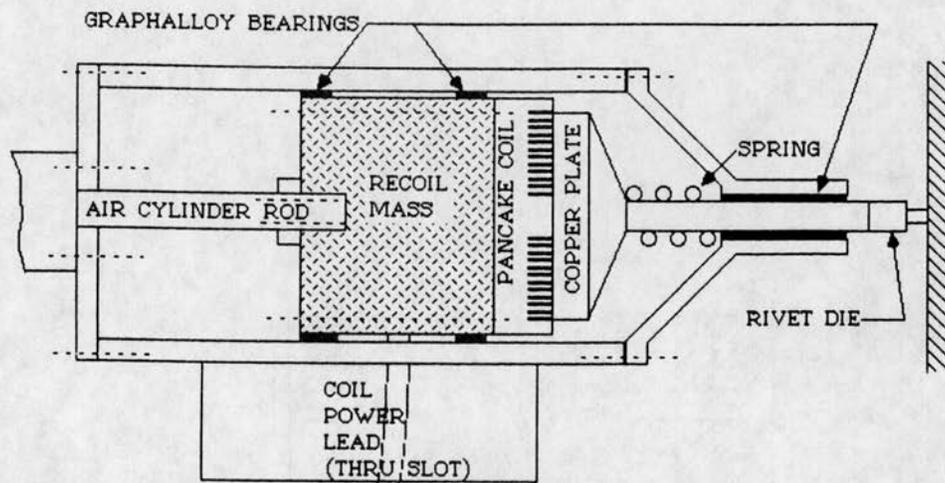
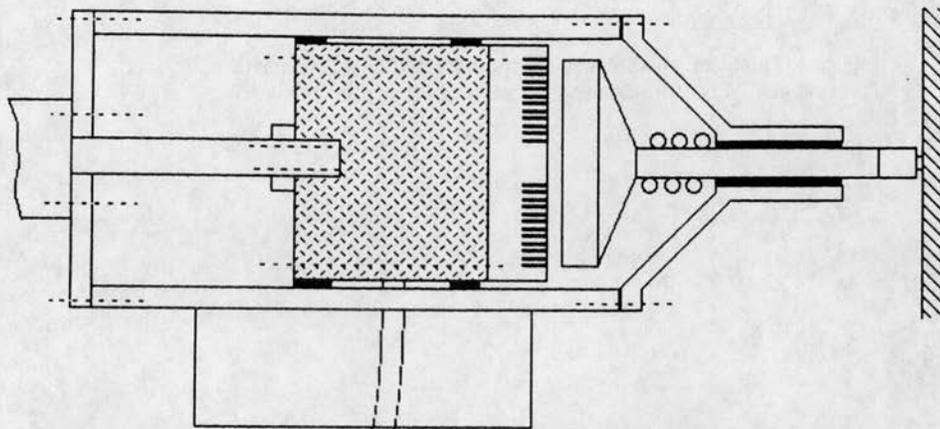


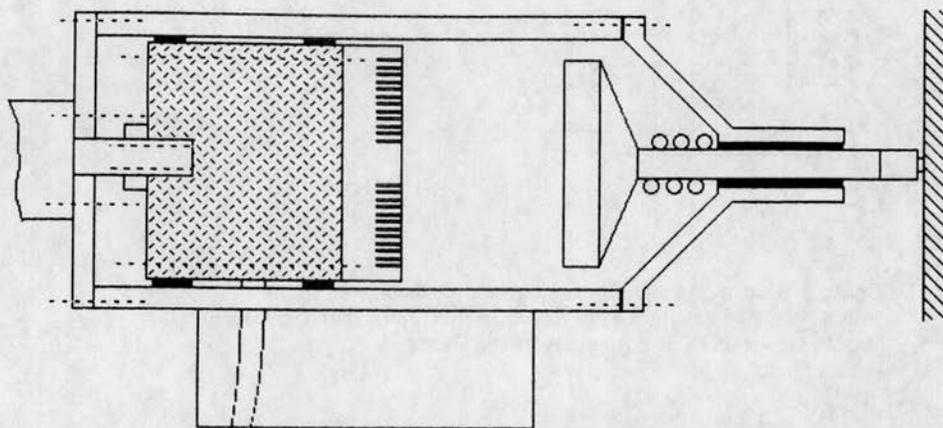
Figure 2 Slug rivets installed by hydraulic squeeze or EECDR in both a flush and double button configuration. Note that significant plastic flow occurs on both sides of the rivet.



MOUNT TO POSITIONING ARM
The LVER in position to deliver a 70 kNt force pulse.



The power stroke is completed in approximately 1 msec. The recoil mass is set in motion but moves only a small distance in this time.



The recoil mass is pneumatically braked to a stop in approximately 100 msec.
Figure 3 Operating sequence of the LVER recoil control system.

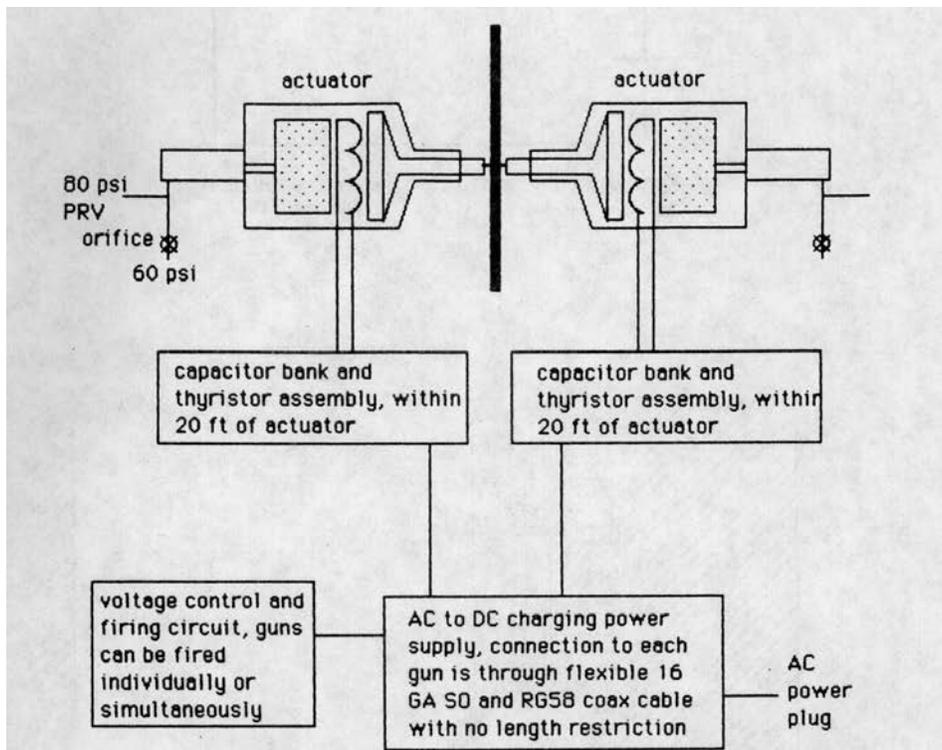


Figure 4 Block diagram of low voltage electromagnetic riveter (LVER).

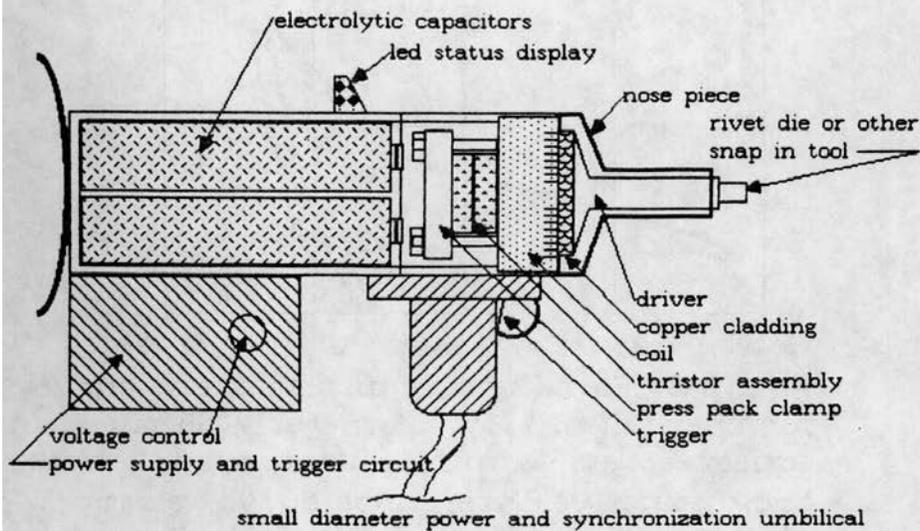


Figure 5 Portable LVER concept with internal power supply.

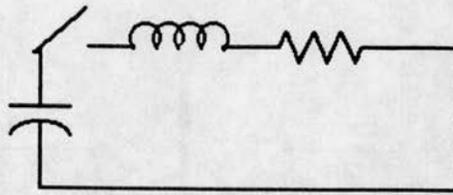


Figure 6 Second order capacitor discharge circuit model.

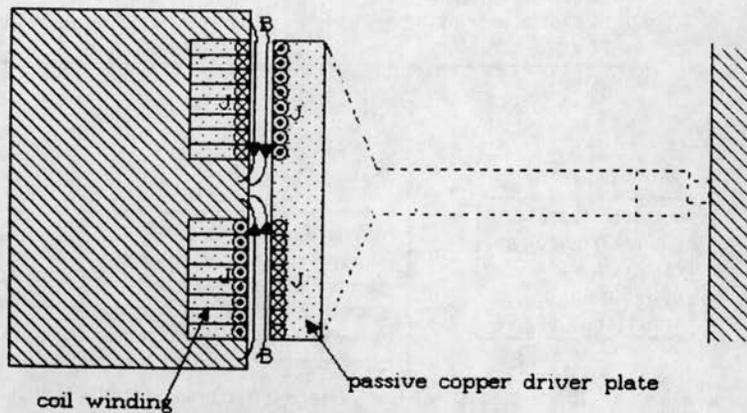


Figure 7 The copper driver plate concentrates the coil flux into the gap. Initially the gap field runs purely transverse to the coil and driver.

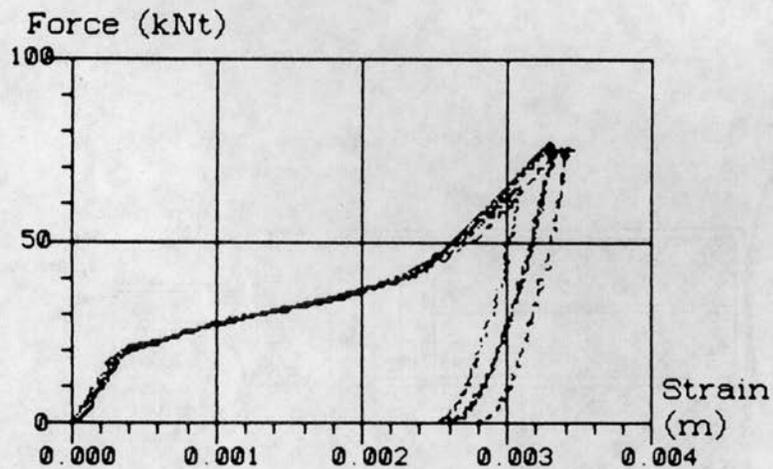


Figure 8 Force versus displacement curve for one half of 5/16" diameter 7050 rivets in squeeze press forming button heads. Note the distinctive three slope curve: elastic, plastic and hydrostatic regimes. Curves from four different rivets are shown.

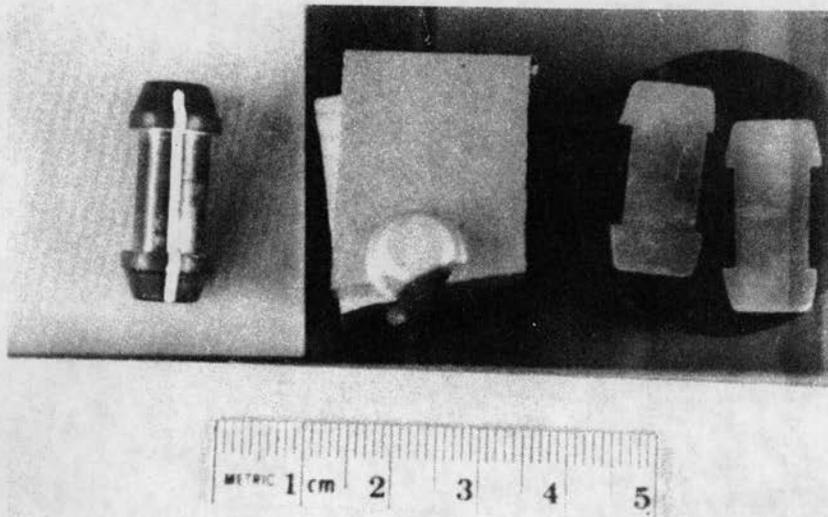


Plate 1 Rivet samples formed by the LVER in various stages of the mounting and polishing process.



Plate 2 Photomicrograph (50x) of a polished 7050 rivet sample formed by the LVER. Shown is the inside corner beneath the button head, the region of maximum shear. A metallurgically acceptable flowline is formed.

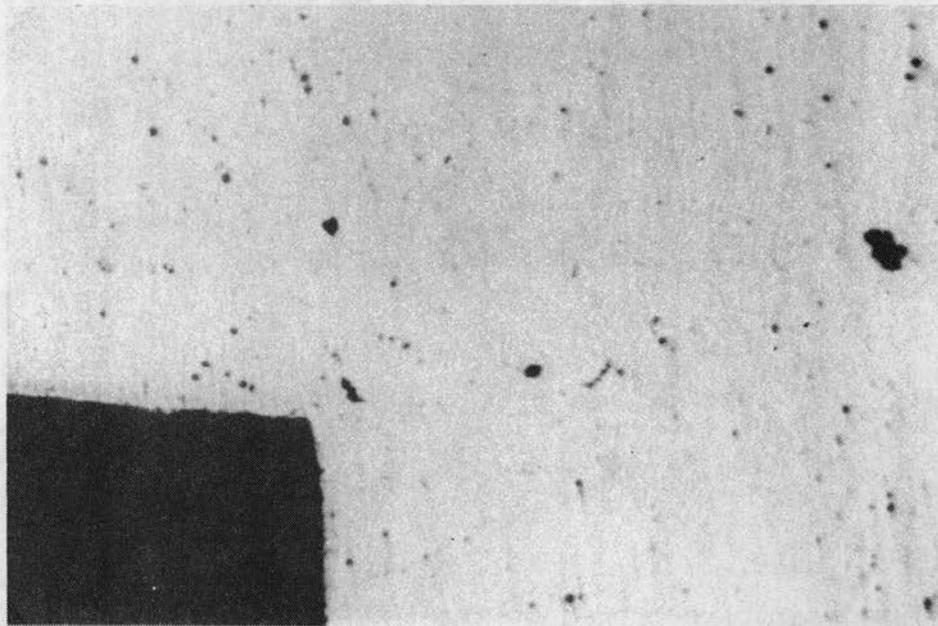


Plate 3 Photomicrograph (50x) of a polished 7050 rivet sample formed by hydraulic squeeze. Shown is the inside corner beneath the button head, the region of maximum shear. The shear band is extremely broad so that no flowline is visible.