An Electromagnetically Driven Metalworking Press*

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Abstract

A small press operated by electromagnetic repulsion and driven by a pulse power supply was constructed at The Ohio State University. This design that applies kinetic energy rather than static force to do work on materials is much lighter and potentially much less expensive than traditional hydraulic, mechanical or servo presses. Performance of the kinetic press is compared to traditional presses in the applications of powder compaction and forming. The results tend to indicate that modest impact speeds of 3 to 18 m/s can improve performance in these manufacturing operations as compared to traditional low-speed machines.

Keywords

Manufacturing, forming, powder

1 Introduction

This work explores the potential in several applications of equipment that is based on kinetic energy instead of static forces. This work will show that because forces are resisted for very short periods of time, modestly sized dynamic equipment can do the work of much more massive equipment [1].

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This paper first reviews the pertinent background in dynamic presses, design of an electromagnetic press and operational characterization procedures are introduced next, followed by short reports of common materials processing operations that could be carried out with a kinetic press. Finally conclusions are given.

2 Background

2.1 Kinetic Presses

While most presses are designed to transmit forces that vary slowly with time onto a workpiece to form, cut or consolidate, another approach is to impart kinetic energy to a ram and use the kinetic energy to perform the operation, in a manner similar to a hammer. Possibly the earliest common use of this approach is represented by the gravity-based drop hammer approach. The basic concept of this and other kinetic presses is shown in Figure 1.

Here a ram of a given mass is accelerated over a relatively long distance (from the x=0 to x=c position) using a modest force and then interacts with the workpiece over the distance x=c to the final point, f.

$$\int_{x=0}^{x=c} F_{in}\, dx = \int_{x=c}^{x=f} F_{out}\, dx \qquad (1)$$

This provides the same kind of mechanical advantage that is used in hammers and allows much greater output forces, F_{out} as compared to the input force, F_{in}. This can allow great force to be transmitted to a workpiece using very simple and lightweight presses.

Another characteristic of this mode of forming is that deformation can take place at relatively high strain rates. The formation of channel-like features in sheet metal as considered in Figure 1 is developed from a flat sheet and this feature has a depth, d, and requires and produces an average Mises strain, $\bar{\varepsilon}$.

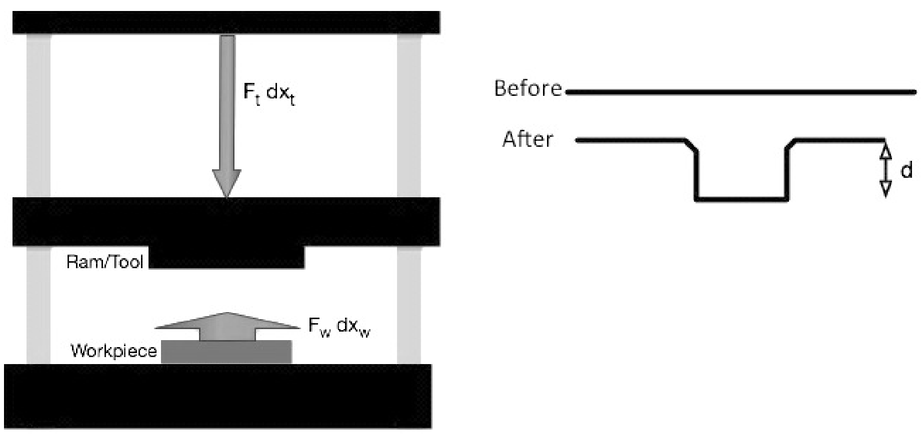

Figure 1: *Schematic representation of a kinetic press created by press with ram/tool impacting workpiece. Schematic of flat sheet before and after forming in feature of depth, d.*

The approximate averaged strain rate that will be developed can be represented as:

$$\dot{\varepsilon} \approx \frac{\bar{\varepsilon}}{\Delta t} \approx \frac{\bar{\varepsilon}\, v_{\max}}{2d} \qquad (2)$$

where Δt is the approximate time duration of the forming process and v_{max} is the speed of the punch or tool at impact. For example if a feature is 1mm deep and this produces an average Mises strain of about unity, a typical press which typically have speeds well under 10 cm/s will produce a strain rate under 25 s^{-1}, whereas a punch speed of 10 m/s will give a strain rate near 2.5 x 10^3 s^{-1}, and a punch speed over 100 m/s provides strain rates over 2.5 x 10^4 s^{-1}.

These higher strain rates can produce significantly increased material flow strength, increased strain rate sensitivity and the strain-hardening rate may also be increased. Much work shows that material behavior can change markedly at strain rates above about 10^3 s^{-1}.

While impulse-based presses are not typical mainstream items in manufacturing, several companies have produced commercial equipment for cutting, forming and powder consolidation based on these principles. LMC, Inc., uses a spring-driven concept [1] that is claimed to reach forming speeds up to 100 m/s [2], but few details are available in the open literature.

Another approach primarily for use in shearing was brought to market as the Lourdes Press, and later revised and offered as the Netronics Bullet Press [3]. This uses magnetic solenoids to drive a relatively traditional die set to a high speed and punching or shearing is done at relatively high speeds. Whereas traditional punching typically takes place well below 10 cm/s, the Bullet press produces tool speeds up to approximately 4 m/s [4]. This high speed approach has been shown to reduce the energy needed to punch sheet metal and produces reduced burr [5]. The work of Klepaczko, in particular, has provided a compelling and complete picture of how increasing punch speed can reduce the required shearing energy and produce different sheared surfaces as compared to quasi-static shearing [6, 7].

Another company, Morphic [8, 9, 10, 11] has developed a hydraulically driven approach to high strain rate forming. They have focused on the application to forming fuel cell plates and while details are not readily apparent in technical journals, from the patents and other public statements, it is clear that the approach again relies on high velocity impact (often simultaneous balanced by impact from both sides of the workpiece, to reduce vibration and need for large systems) and from this generates high pressures, with claims up to “4 GPa in a fraction of a second” [12]. While it appears this technique is commercial, or in the early stages of commercialization, there is little detailed information on the speeds reached by this equipment or on the effects on formability or shearing.

3 The OSU Electromagnetically Driven Press

3.1 Design and Construction

In order to test the capabilities of a modest-velocity kinetic press, a simple electromagnetically driven metalworking press was designed and built at The Ohio State University. The EM press utilizes a 4 turn planar spiral primary copper coil with a 165mm outside diameter closely coupled to an aluminum flyer assembly of the same diameter that slides in a bushing arrangement. The coil, flyer, workpiece and platen are shown in schematic form in Figure 2. A pulse from the capacitor bank through the primary coil induces an opposing current in the aluminum flyer, resulting in strong Lorentz force that accelerates the flyer assembly away.

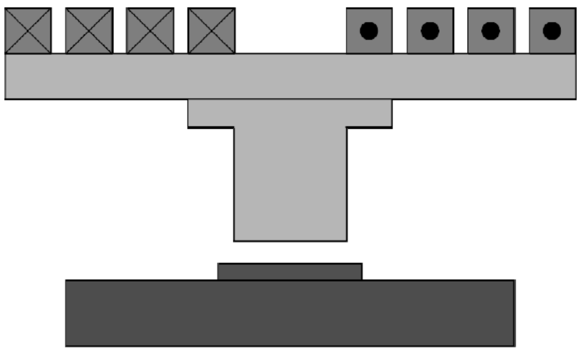

Figure 2: *Schematic representation of the electromagnetic press*

The coil assembly consisted of G10 layers and an embedded spiral copper coil. The coil was waterjet cut from Alloy 18150 copper plate. It was placed within a G10 negative, also waterjet cut to accommodate the complex spiral shape. A section view of the model of this coil assembly with the leads is shown in Figure 3.

The sliding guide arrangement, shown in Figure 4, utilizes lubricated Ultra High Molecular Weight Polyethylene for bushings. Two of the adjacent bushings are backed by brass plates with screws behind them. In this manner, the bushings restrict motion of the tool to translation along the central axis. In addition, the two backed sides can be adjusted to compensate for wear of the bushings over time as the tool is used.

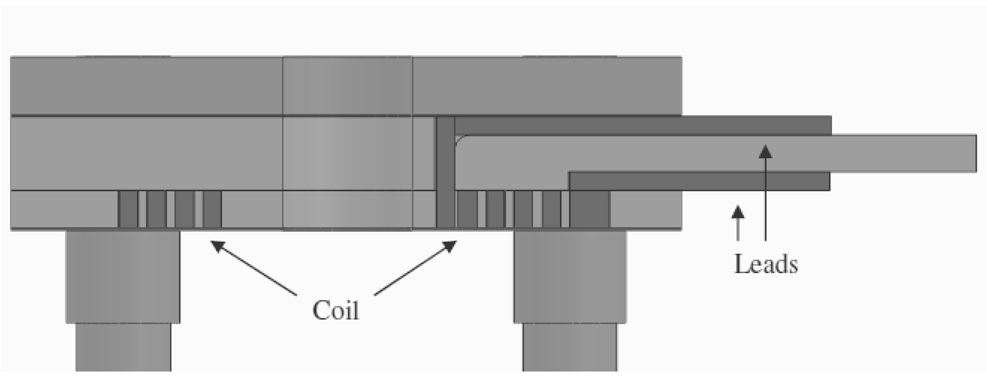

Figure 3: *Coil system showing copper primary coil and reinforced phenolic backing*

The flyer assembly can also be seen In Figure 4. The aluminum flyer is bolted to the tool post that slides in the bushing arrangement and has a stroke distance of up to 18mm.

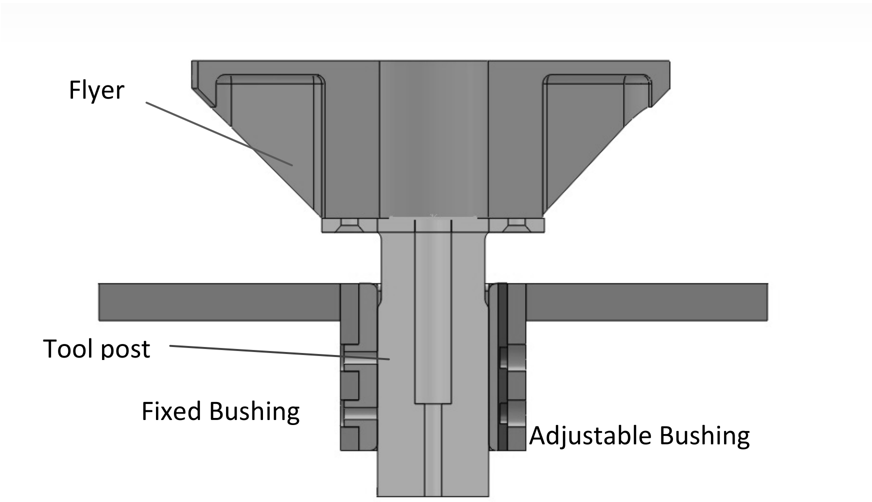

Figure 4: *EM Press bushing, post and flyer assembly section view, with adjustable UHMW bushing on the right*

The tool post has an alignment pattern and hole on the end to allow for interchangeable tooling to be utilized, including adapters to accommodate standardized punch and die equipment. A retraction spring is used to return the tool to its initial position after each stroke. The full EM Press is shown in Figure 5.

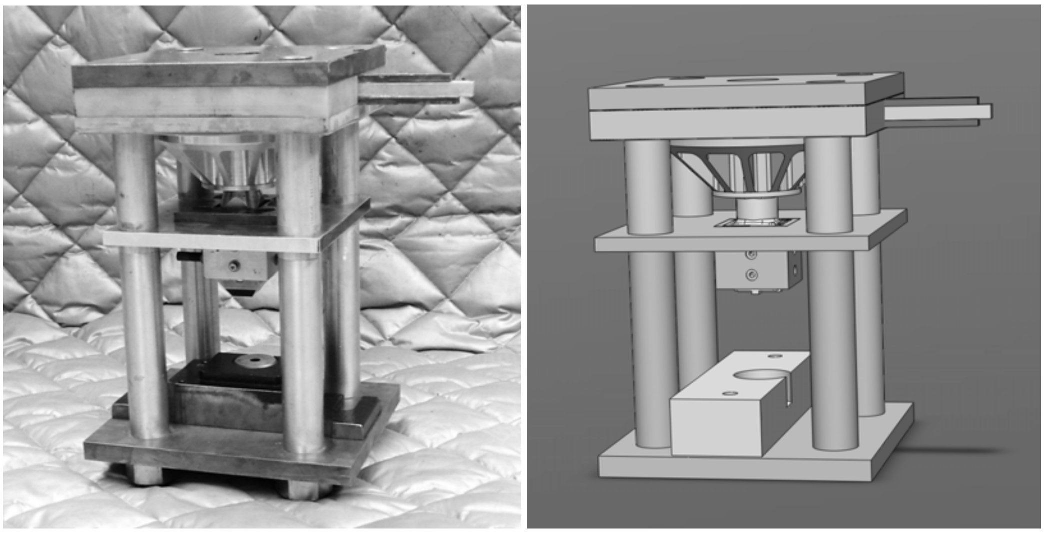

Figure 5: *Actual embodiment of the high-speed press and 3-D CAD rendering.*

3.2 Operational Characterization

Salient variables and process parameters pertinent to the press operation include; electric current in the driving coil, velocity of the flyer/tool post, and moving mass. Primary coil current was recorded with a Rowgowski style current transformer and integrating amplifier [13]. Flyer velocity data was measured by Photonic Doppler Velocimetry [14]. The sum of the masses of moving components in various configurations is easily determined and with the velocity/time history may used to calculate kinetic energy, momentum, force etc.

The input energy to the driving coil was recorded for these experiments in the form of the time varying electric current in the coil. A typical 4kJ discharge results in a peak current of ~100 kA in about 50µs. The time frame of the input pulse to peak current is short (most energy expended in less than 250µs) compared to the duration of ram travel (~ 1.5 milliseconds).

In order to quantify the forces imparted to the workpiece it is necessary to know the velocity vs. time history of the ram motion. To this end, movement of the flyer plate was measured by Photonic Doppler Velocimetry. This technique is well known and discussed elsewhere [14, 15]. Essentially PDV is a laser-based interferometer, the output of which is acquired then reduced to velocity by Fourier transform.

Figure 6 shows a typical flyer plate velocity curve overlaying the driving current. The periodic variation of velocity during flyer travel is the vibrational ringing of the plate. The average velocity over the first millisecond is about 10 m/s.

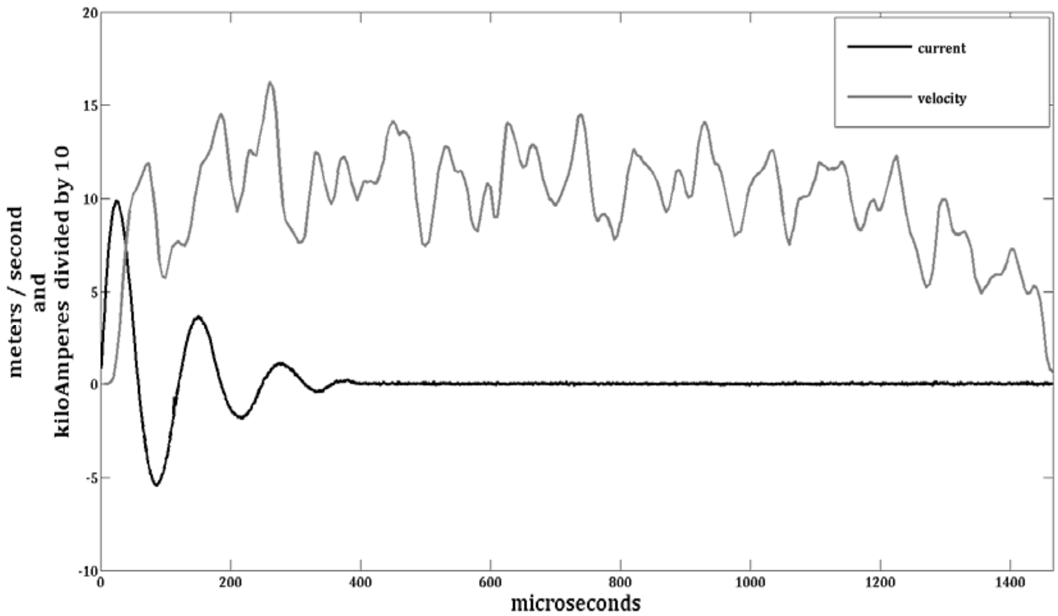

Figure 6: *Launch characteristics of the tool post in a 4 kJ discharge. Peak average velocity is near 10m/s using the flyer shown schematically in Figure 4.*

Ram velocity increases fairly linearly with input energy. Figure 8 is a graph of input energy and velocity. The maximum input energy used was 7.2 kJ resulting is a velocity of 16.1 m/s.

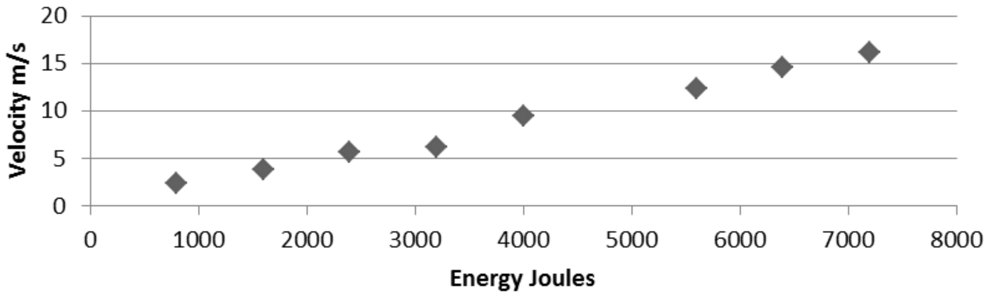

Figure 7: *Ram velocity as a function of input energy using the more robust flyer plate shown in Figure 4.*

4 Applications

The press has been used in a variety of applications. In particular, the processes of powder consolidation, sheet metal forming, coining and shearing have been examined. In this short paper we will highlight applications in powder consolidation and sheet forming.

4.1 Powder consolidation

There is considerable interest in the consolidation of powders. Recent developments allow the production of new classes of low-cost powders that can be effectively consolidated. Work was done by Kabert using the EM press for the consolidation of titanium powders starting with roll compacted sheets of Armstrong processed powder [16]. Figure 8 shows the classical problem, which is that large static pressure is needed to produce densities near the theoretical density. Here we briefly demonstrate the advantages of velocity. Further detail is available in the thesis of Kabert [16].

The EM press may be operated cyclically with the rate limited by the charge time of the capacitor bank and cooling limitations of the coil. In the application of consolidating roll compacted sheets of titanium powder, a flat tool steel attachment with a 38mm square face was attached to the flyer assembly. A flat steel backing block was used as a die. 25mm squares of material were impacted repeatedly with charge energies of 0.96 kJ, 1.28kJ or 1.92kJ. Each sample was struck 20 times at the same energy. Thickness measurements were taken with a ball micrometer after strokes 1, 3, 5, 10 and 20 to observe the results throughout the process. Two different flyers and ram combinations were used. First, a low mass system resembling that seen in Figure 2 was used. This had a total ram and flyer mass of 0.96 kg, but was prone to fatigue damage. A more massive flyer was designed and created from high strength, as shown in Figures 4 and 5. As detailed in Kabert's thesis, at a given capacitor bank discharge energy, these rams had similar kinetic energies, but the lighter system had higher velocity.

Results for compaction of roll-compacted commercial purity and 6Al-4V titanium powders are marked respectively CPARM and 64 ARM in Figure 9. Both the light (flyer 1) and heavier flyers were used and multiple strokes were used to compact the powders. These results show two things clearly: 1) that significant consolidation is possible with this approach using multiple strokes, reaching densities that would be require well over 500 MPa in conventional compaction and 2) increasing velocity is more important than increasing kinetic energy. Significantly higher compaction densities were seen with the less massive flyer at higher velocity, when launched with the same energy.

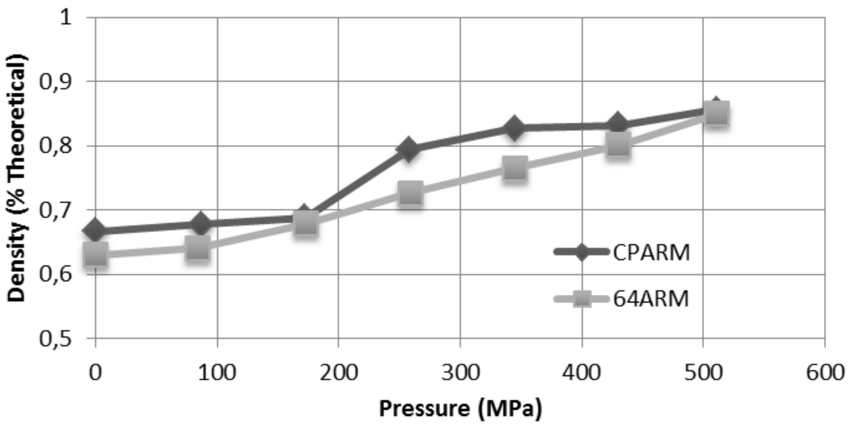

Figure 8: *Density as a function of pressure for the compaction of partially-dense roll compacted sheet in compression between flat platens. CPARM refers to commercial purity powder, and 64 is a Ti-6Al-4V alloy, both from the Armstrong powder production method.*

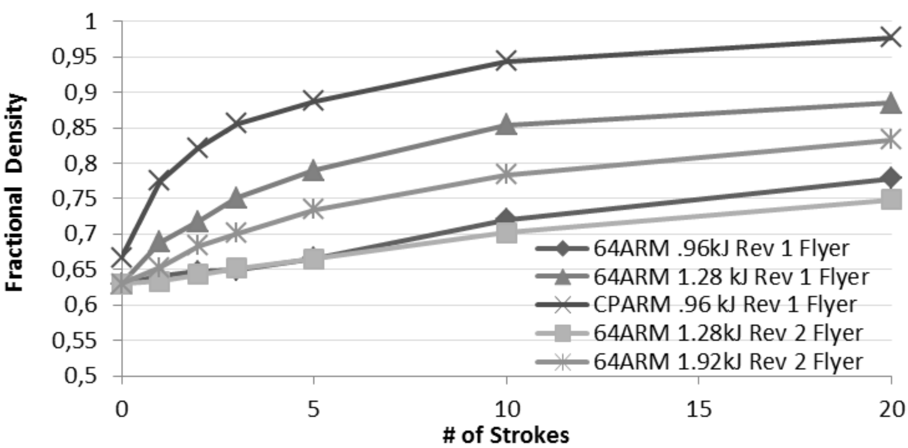

Figure 9: *Compacted densities as a function of number of strokes for roll compacted partially dense titanium sheets.*

4.2 Sheet metal forming

Single-Sided die urethane pad sheet metal forming with the EM press has been investigated by Windholtz [17] by plane-strain stretch forming into a channel. This shape is exemplified in many important practical features – stiffening ribs in structural parts, heat exchangers and fuel cell plates. Again, a short example of some results from a more comprehensive forthcoming M.S. thesis is shown here. In that work, a range a velocities and materials were considered in channel forming. Figure 10 shows 0.381 thick H-19 3003 aluminum formed into a sinusoidal die using a polyurethane pad. Both a simple steel die was used, and one coated with BN lubricant. For both a quasi-static press and the high-speed press the force or energy was increased just to the point where failure was seen and the greatest depth that could be obtained without failure was sought. Results from that study are shown below. In all cases, the urethane pad effectively locked the sheet to the flat surface of the die and all deformation was in near plane-strain stretching. The electromagnetic press formed aluminum sheet to a 30% greater depth before failure compared to static methods of urethane pad forming, and there was a similar increase in strains to failure. Impact velocity was about 10 m/s. Figure 10 shows cross sectional views of the formed metal and dies under different conditions.

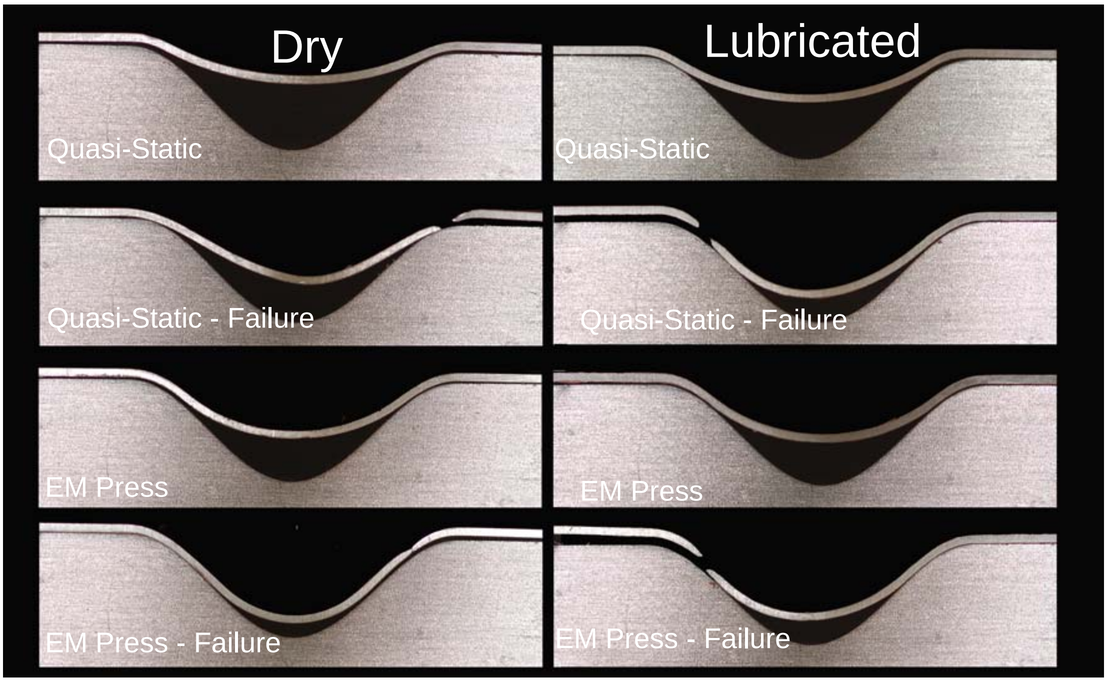

Figure 10: *Cross-sections of 3003 H-19 aluminum stretched into channels in nearly plane strain using a urethane pad and a one-sided steel die. Conditions with inputs just prior to and just after failure are noted in each case.*

5 Conclusions & Issues

In several operational respects the electromagnetic press is comparable or superior to methods based on other types of equipment. In particular, this work demonstrated enhanced plasticity of sheet aluminum by urethane pad forming in comparison to quasi-static methods and improved consolidation in high speed impact pressing versus quasi-static conventional pressing.

There are high accelerations associated with this device that induce severe shock loads to the apparatus. For example, a 4kJ input to the driving coil accelerates the tool post to 10m/s in about 50µs, which is 200,000G. In the application of coining, acceleration on impact can be more than double that. Such loading must be considered in the design in order to minimize fatigue and stress concentrations. Work in improving the robustness of this class of equipment is underway.

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