Control of Velocity, Driving Pressure, and Planarity During Flyer Launch with Vaporizing Foil Actuator[*]

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Abstract

Electrically-driven rapid vaporization of thin conductors produces a high-pressure pulse which can be used to accelerate thin metal sheets to high velocities. Recently, vaporizing foil actuators (VFA) have been applied toward a variety of impulse-based metalworking operations such as collision welding, closed-die forming, embossing, and shearing. To better apply VFA to different purposes, it is necessary to develop an understanding of how variations on the characteristics of the foil actuator affect its mechanical impulse generation. In this work, actuators made out of 0.0508, 0.0762, and 0.127 mm thick full hard temper AA1145 foil were used to launch 0.508 mm thick AA2024-T3 sheets toward a photonic Doppler velocimeter (PDV) probe. Launch velocities ranging between 300 and 1000 m/s were observed over a distance of less than 3 mm, and repeated trials demonstrated repeatable results. Velocity, current and voltage traces were used to examine the effect of deposited energy on average pressure and resulting velocity for foil actuators of various thicknesses. The planarity of the flyer sheets' launch and flight was demonstrated with 0.0762 mm foil actuators by experiments that employed multiple PDV probes simultaneously recording the velocity evolution at different locations across the surface of the flyer.

Keywords

Impulse metalworking, Collision welding, Vaporizing foil actuator (VFA)

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1 Introduction

Rapid discharge of a high voltage through a thin metal conductor results in the rapid vaporization of the conductor, creating a high-pressure pulse around it as the gases expand. Typically, the source of the electrical discharge is a capacitor bank, and the conductor is a thin foil or wire, referred to in this work as a vaporizing foil actuator (VFA). The impulse produced can be used to accelerate metal workpieces to velocities on the order of 1 km/s, within a distance of only a few millimeters.

Vivek et al [1], [2], [3] have applied this phenomenon as a tool for collision welding of dissimilar materials, as well as other impulse metalworking applications such as closed-die forming, embossing, coining, tube expansion, high-speed shearing, and springback calibration. Some of the results of this work are shown in Figure 1. Since the quality of these processes depends largely on control of the velocity of the workpiece, it is necessary to gain a better understanding of the development of the pressure pulse and how it can be optimized for different applications by changing the input parameters of the VFA technique.

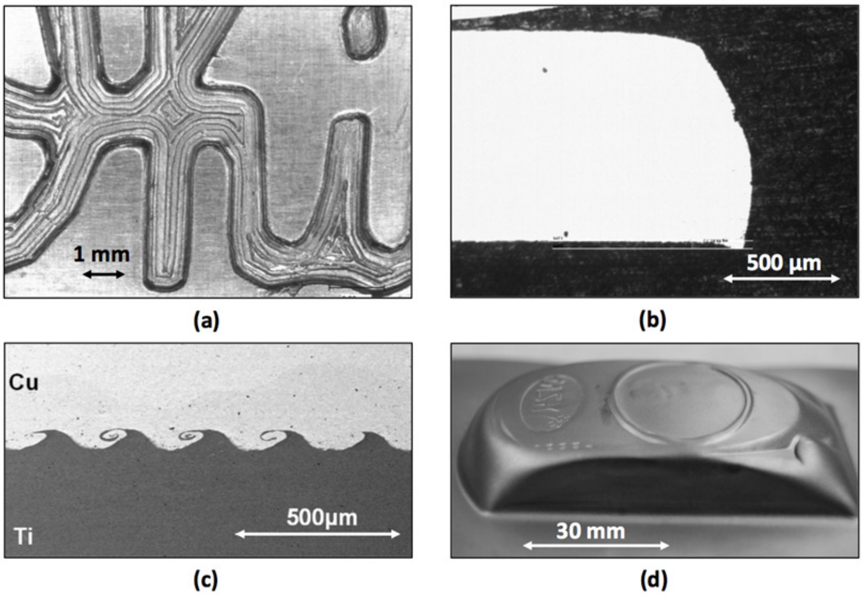


Figure 1: *(a) Embossing/coining, (b) burr-free shearing of high-strength steel, (c) VFA weld interface, (d) closed-die forming.*

Though the use of vaporizing conductors for impulse metalworking is a recent development, the phenomenon (often referred to as exploding conductors) has been known for some time. In 1962, Keller and Penning [4] used vaporizing foils to drive thin dielectric flyers into targets at more than 4 km/s, reaching impact pressures of up to 10 GPa. In 1980, Chau et al. [5] reached flyer velocities of 20 km/s and pressures of over 500 GPa, by adding a metal layer to the dielectric flyer; the increased shock impedance of the metal resulted in much higher impact pressures. That system has been used to study high-pressure impacts, including the shock initiation of explosives. Vaporizing wires have also found limited use in industry with electrohydraulic forming; however, as noted by Daehn [6], their use has proven difficult to commercialize.

This work was specifically performed under the parameters of VFA-driven collision welding (referred to as VFAW), in which the pressure pulse accelerates one metal sheet (the flyer) across a short standoff distance, as illustrated in Figure 2(a). The ideal impact velocity and impact angle (which is a function of standoff distance in the current welding setup) vary among different metal pairings to be joined; therefore, it is desirable to be able to predict the evolution of flyer velocity. This work investigates how, across a range of input energies, variations in foil thickness affect the evolution of velocity of the flyer sheet. It goes on to relate the current density at the time of vaporization to the velocity of the flyer.

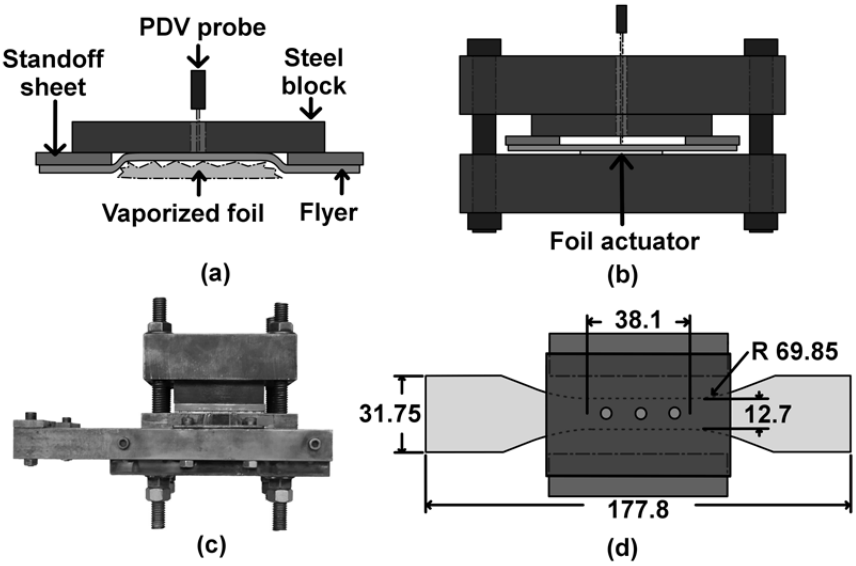


Figure 2: *(a) Side view during flyer launch, (b) side view of experimental setup, (c) actual experimental fixture, (d) top view of foil actuator setup, dimensions in mm.*

The work of Grigoriev and Pavlenko [7] demonstrated that the magnitude of the pressure pulse produced by a vaporizing foil is proportional to the energy deposited in the foil at the time of vaporization. This energy E_d can be calculated as the integral with respect to time of the product of current I and voltage U, to the vaporization time t_v:

$$E_d = \int_0^{t_b} I(t)U(t)\,dt \tag{1}$$

The average pressure pulse P_{av} can be calculated by the following equation, where ρ_f is flyer density, h_f is flyer thickness, V_2 and V_1 are impact and initial flyer velocities, and t is the time from vaporization to flyer impact against the target:

$$P_{av} = \rho_f h_f \frac{V_2 - V_1}{t} \tag{2}$$

Chau et al. [5], who used the electrical Gurney model proposed by Tucker and Stanton [8], showed that the final velocity V_f of a flyer plate launched by a vaporizing foil can be related to the square root of the vaporization current density J_B, where K and b are empirically derived, and M/C is the ratio of foil mass to flyer sheet mass:

$$V_f = \left(KJ_B^b\right)^{0.5}\left(\frac{M}{C} + {}^1\!/_3\right)^{-0.5} \tag{3}$$

Cho et al. [9] concluded that more energy is deposited into a vaporizing wire when the current rise time – the time by which the current reaches its peak value – is shorter, resulting in a greater amount of the conductor being vaporized.

Previous experiments with copper and aluminum vaporizing wires by Vivek et al. [2] indicated that the conversion from electrical to kinetic energy upon vaporization is much more efficient in aluminum. Contributing to the greater pressure produced by vaporizing aluminum is the exothermic reaction forming alumina, which is on the same time scale as the flyer launch. Aluminum is therefore considered to be the preferable material with which to construct vaporizing foils.

2 Experimental Parameters

The experimental setup is pictured in Figure 2(b) and (c). The foil actuator was electrically insulated on each side with polyimide tape, except for the ends, which were fixed to copper terminals leading to a capacitor bank. The faces of the flyer sheet and the steel base that touched the foil were also insulated with polyimide tape to prevent current flow through the fixture or the flyer plate. The flyer was centered over the narrow section of the foil. Standoff sheets were placed on the edges of the flyer, parallel to the length of the foil, to separate the flyer at a distance from the steel backing blocks.

All flyer sheets were 76.2 mm square, cut from 0.508 mm thick T3 temper AA2024. The standoff distance between the flyer and the backing block was 2.5 mm in all cases.

The design of the foil actuators is pictured in Figure 2(d). Since the vaporization is initiated where the current density is highest, the foils are designed with a narrow section under the workpiece, to ensure that the pressure pulse occurs there. These were cut from 0.0508, 0.0762, and 0.127 mm thick full hard temper AA1145. The foils of each thickness were cut from their parent rolls along the same direction. Each foil thickness was tested at 2, 4, 6, and 8 kJ input energies from the 8-capacitor bank, the parameters of which are listed in Table 1. Each of these trials was performed twice.

C	L	R	Max. charging voltage	Max. charging energy	Short-circuit current rise time
426 μF	100 nH	10 mΩ	8.66 kV	16 kJ	12 μs

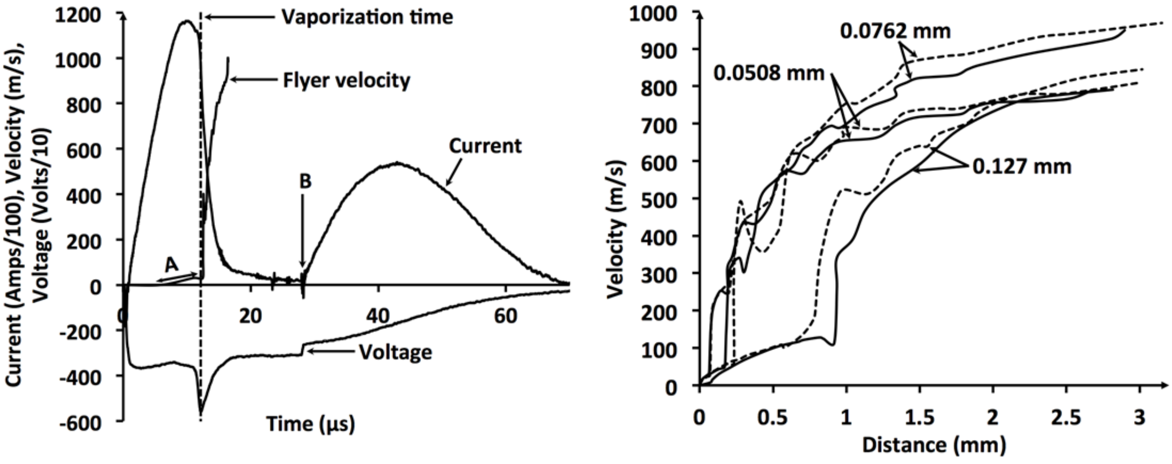
Table 1: *Electronic parameters of the capacitor bank.*

The evolution of flyer velocity over time was recorded through a hole in the center of the top of the fixture, using a photonic Doppler velocimetry (PDV) system capable of measuring velocities up to 2 km/s. PDV is a technique for measuring high velocities, developed by Strand et al [10]. In 2009, Johnson et al [11] demonstrated the use of PDV as a diagnostic for impulse metalworking operations. In this technique, light from a laser probe is directed perpendicularly onto the surface of the workpiece in motion; the probe collects the light reflected back from the surface, which is Doppler-shifted. This is mixed with non-Doppler-shifted light, creating a measurable beat frequency that is directly proportional to velocity. An oscilloscope simultaneously recorded the velocity, current and voltage at a sampling rate of 5 GHz. Current was measured using a 100 kA:1 V Rogowski coil, and voltage was measured using a 1000:1 voltage divider.

To investigate the planarity of the flyer sheet launch, three trials were performed using 0.0762 mm thick foils at input energies of 4, 6, and 8 kJ. In each of these tests, three PDV traces were recorded simultaneously, using the voltage spike as the trigger for the oscilloscope. The three PDV probes were positioned 15 mm apart from each other, for a total spread of 30 mm along the length of the narrow section of the foil (referred to as the active area), as illustrated in Figure 2(d).

3 Results and Discussion

Figure 3(a) combines velocity, current, and voltage traces for a trial using a 0.0762 mm thick foil at 6 kJ input energy. A notable feature is the region of acceleration to low velocity, marked *A* in the figure. This was the result of the countercurrent induced in the workpiece by the current in the foil: the opposing electromagnetic fields repelled the flyer from the (immobile) foil. At its end is the voltage spike, which signifies the point at which the foil vaporized. Webb et al. [12] explain this: as the foil vaporize, its resistance increases abruptly, causing the voltage spike. As the vapor expands and cools, it begins to conduct again, discharging the remaining energy in the system, which produces the wide peak in the current trace starting at the time marked *B*.



(a) **(b)**

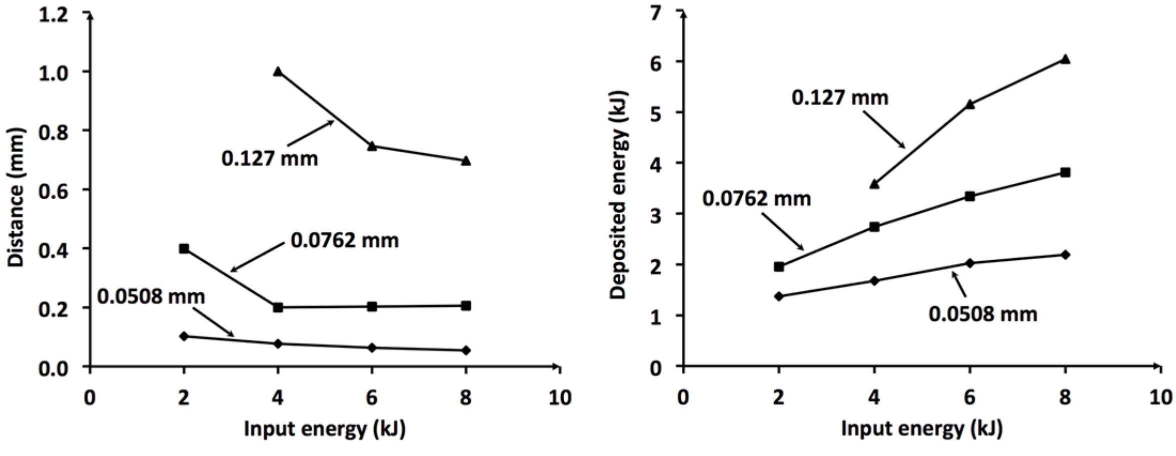
Figure 3: *(a) Current, velocity, and voltage vs. time for 0.0762 mm foil at 6 kJ input energy, (b) velocity vs. distance traveled from foils at 6 kJ input energy.*

To obtain the velocity at many different possible welding standoff distances, the velocity vs. time data from the PDV was integrated in order to plot velocity vs. distance traveled. Figure 3(b) compares the traces for the three foil thicknesses at 6 kJ input energy. Traces produced by repeated trials overlapped with one another fairly well, indicating the repeatability of the launch process – though additional sets of trials will be necessary to demonstrate this with confidence.

It can be noted in Figure 3(b) that the measured distance traveled was greater than the standoff distance of 2.5 mm. This was because a circular plug of the flyer was sheared off through the hole in the backing block through which the PDV probe measured flyer velocity. The velocity of this plug continued to be recorded until it rotated enough to no longer reflect laser light back to the probe.

In Figure 3(b), it can be also seen that the region of electromagnetically driven low acceleration was much larger for the 0.127 mm foils than for the other two foil thicknesses. The flyers driven by the 0.127 mm foil traveled nearly 1 mm away from the foil before the vaporization occurs, while the others moved less than 0.25 mm. This occurred largely because the thicker foil – having approximately twice the mass of the other two – required a longer time before the current density increased enough to vaporize the metal. In fact, at lower input energies, the thicker foils melted rather than vaporized, since there was not enough energy to exceed their enthalpy of vaporization. This occurrence is important to consider in application to impulse metalworking because the large movement of the flyer sheet away from the foil lessened the confinement of the pressure pulse, reducing the potential driving force behind the flyer launch. Additionally, for metalworking requiring acceleration distances on the order of 1 mm, this behavior would not be suitable, since the flyer would reach its target before significant acceleration occurred.

Figure 4(a) shows the average distances traveled by the flyer before vaporization for all foil thicknesses and input energies. (Note: there is no data point for 0.127 mm foil at 2 kJ because the deposited energy was not enough to vaporize it.) It can be seen that the pre-vaporization distance decreases somewhat with increasing input energy. This is because the rise time of the capacitor bank remained approximately 12 μs even as its charging energy was increased. Therefore, the rate of energy deposition increased and the energy density necessary to vaporize the foil was reached more quickly, leaving less time for the electromagnetic repulsion to affect the workpiece.



(a) (b)

Figure 4: *(a) Distance traveled before vaporization vs. input energy, (b) energy deposited before vaporization vs. input energy.*

Figure 4(b) shows how the average energy E_d deposited in the foil actuator before the vaporization – integrated from the current and voltage vs. time traces, as according to Eq. (1) – varied with input energy for each foil thickness. The energy deposited in the conductors increased with increasing input energy from the capacitor bank; however, the increase was not linearly proportional. This indicates that, while faster energy deposition improves the energy density in the foil at vaporization, there is a limit to how much energy can be deposited in a foil of a given mass. Foils of greater mass display the potential for greater energy deposition, as may be expected.

Figure 5(a) shows the average flyer velocity at a distance of 1.6 mm, which was a standoff distance used in preliminary vaporizing foil collision welding experiments. Average flyer velocity showed a similar trend toward non-linear increase with increasing input energy. In spite of the greater deposited energy in the 0.127 mm thick foils, these produced the lowest flyer velocities.

The lower velocity can be partially attributed to the reduction in confinement pressure due to the observed significant electromagnetic push. Also contributing to the lower velocity was the much greater mass of aluminum – more than double that of the other foils – being vaporized. Although the deposited energy was greater for the thicker foils, the vaporization current density was lower than for the thinner foils. It appears, however, that, if the input energy were increased further, or the energy deposition rate were increased through faster capacitors, the thicker foils have the potential to produce greater flyer velocities.

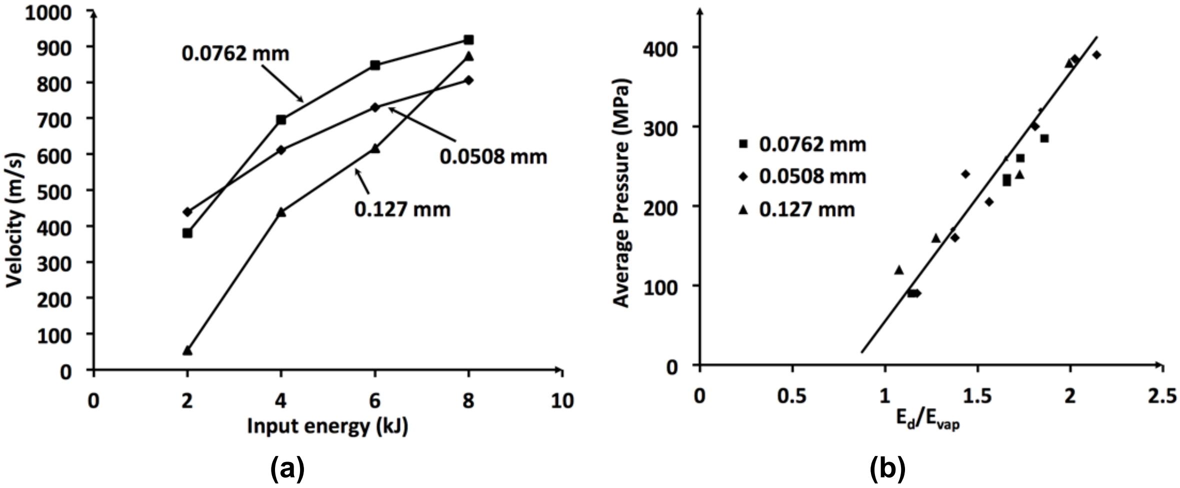


Figure 5: *(a) Flyer velocity at 1.6 mm vs. input energy, (b) average driving pressure vs. the ratio of deposited energy to energy of vaporization for a given foil.*

In order to completely vaporize the aluminum foil, heat has to be supplied to raise the temperature to melting point, to melt the given mass, to raise the temperature of melted mass to boiling point, to vaporize the liquid, and to raise the temperature of the gas to 2793 K (boiling point of aluminum). According to Osher et al [13], the total heat needed for this is 356 kJ/mol. Taking the active area of the foil to be the relevant portion of the mass being vaporized, the energy E_{vap} necessary to vaporize this section is calculated to be 1.478, 2.191, and 3.643 kJ, respectively, for the 0.0508, 0.0762, and 0.127 mm thick foils. Figure 5(b) plots the average pressure P_{av}, as calculated by Eq. (2), against the ratio E_d/E_{vap}. The velocities V_1 and V_2 were found from the velocity vs. distance curves, such as Figs. 4 and 5. V_1 was the velocity when the vaporization occurred, and V_2 was the velocity at 2.5 mm. A linear trend is observed, enabling the following empirical relationship to be obtained for this specific system (P_{av} in MPa):

$$P_{av} = 345.79\left(\frac{E_d}{E_{vap}}\right) - 223.75, \textit{ correlation} = 0.9385 \tag{4}$$

An attempt was made to relate terminal flyer velocity to vaporization current density, as in Eq. (3). However, due to the non-uniform shape of the foil actuators, which are designed specifically to induce current crowding in the narrow region, it proved difficult to accurately calculate the vaporization current density. An estimate was attempted, assuming the current density to be constant throughout, but a plot of terminal velocity against the estimated current density displayed no apparent trends.

Figure 6 depicts the flyer displacement over time, integrated from velocity vs. time, for the three launch planarity experiments. The three probes are identified by their location above the foil's active area, relative to the RLC circuit: one on the end closest to the negatively charged terminal of the capacitor bank, one in the center of the active area, and one closest to the ground side of the bank.

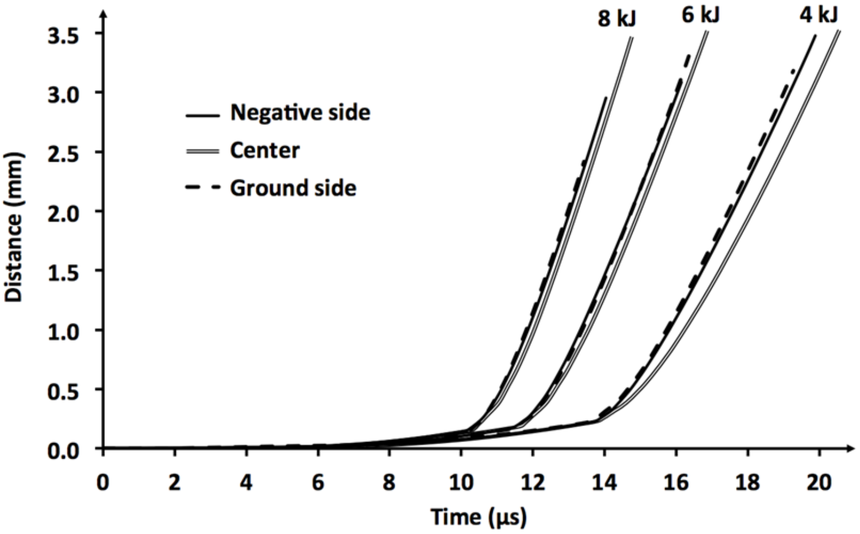


Figure 6: *Flyer displacement vs. time for 0.0762 mm thick foils.*

The time delay before launch decreased with increasing input energy due to the effect described above; that is, the rate of energy deposition into the circuit increases with increasing charging energy on the capacitors. It can be seen that the flyer launch was very nearly simultaneous across the active area at higher input energies, where E_d/E_{vap} is larger. The distance traces for the ends of the active area are nearly indistinguishable from one another, while the center lags behind by about 0.2 µs, or about 0.5 µs for the 4 kJ trial. This is due to a phenomenon termed "end effect." The vaporization is most likely to initiate where the change in current density is the highest, which for these foil actuators is the ends of the straight section. This effect can be reduced or eliminated by refining the shape of the foil actuators.

Additional trials using flyer sheets of materials of different densities, alloys, and tempers would be required to decidedly verify that, irrespective of flyer material, the relationship between average driving pressure and the energy ratio is linear.

4 Results and Discussion

- Vaporizing foil actuators can be used to consistently launch AA2024 sheet metal flyers on the order of 0.5 mm thick to velocities between 300 and 1000 m/s within distances from 0.25 to 3 mm. The velocity reached at a certain distance can be reliably controlled by jointly or separately varying the VFA thickness and the input energy.
- The fundamentals of the VFA method are not expected to change when parameters are varied. Though a faster current source and resultant greater pre-vaporization energy deposition, E_d, may be preferable, the proportionality of the relationship between the ratio E_d/E_{vap} and the vaporization pressure remains linear. This relationship holds true regardless of foil thickness.
- The ideal foil thickness and shape is dependent on the intended application. Thicker foils require more input energy to vaporize, better pressure confinement in the setup, and a greater acceleration distance, but appear to have the potential for greater final flyer velocities given greater current density. The temporal development of pressure from thinner foils was more suitable for the VFA welding setup used in these experiments, in which a shorter acceleration distance is preferable and greater workpiece velocity is not necessary.
- The flyer sheet launch and flight are fairly planar across the active area of the foil, with a < 0.5 μs delay in the center as compared to the edges. The delay is reduced when E_d/E_{vap} is increased. The lag in the center can be compensated for by redesigning the foil actuator to eliminate the end effect.

References

[1] Vivek, A., Hansen, S.R., Liu, B.C., and Daehn, G.S.: “Vaporizing Foil Actuator: A Tool for Collision Welding,” *Journal of Materials Processing Technology*, **213**(12), 2013, pp. 2304-2311.

[2] Vivek, A., Taber, G.A., Johnson, J.R., Woodward, S.T., and Daehn, G.S.: “Electrically Driven Plasma via Vaporization of Metallic Conductors: A Tool for Impulse Metal Working,” *Journal of Materials Processing Technology*, **213**(8), 2013, pp. 1311-1326.

[3] Vivek, A., Brune, R.C., Hansen, S.R., and Daehn, G.S.: “Vaporizing Foil Actuator Used for Impulse Forming and Embossing of Titanium and Aluminum Alloys,” *Journal of Materials Processing Technology*, **214**, 2014, pp. 865-875.

[4] Keller, D.V. and Penning, R.J.: “Exploding foils – The Production of Plane Shock Waves and the Acceleration of Thin Plates,” *Exploding Wires*, W. Chase and H. Moore, eds., Plenum Press, **2**, 1962, pp. 263-277.

[5] Chau, H.H., Dittbener, G., Hofer, W.W., Honodel, C.A., Steinberg, D.J., Stroud, J.R., Weingart, R.C., Lee, R.S.: “Electric Gun: A Versatile Tool for High-Pressure Shock Wave Research,” Review of Scientific Instruments, **51**(12), 1980.

[6] Daehn, G.S.: “High Velocity Metal Forming,” *ASM Handbook*, **14B**, ASM International, 2006, pp. 405-418.

[7] Gregoriev, A.N., and Pavlenko, A.V.: “Pressure Generated by the Electric Explosion of Metal Foils,” *Technical Physics Letters,* **25**(9), 2009, pp. 865-868.

[8] Tucker, T.J. and Stanton, P.L.: “Electrical Gurney Energy: A New Concept of Modeling Energy Transference from Electrically Exploded Conductors,” SAND-74-0244, Sandia National Laboratory, Albuquerque, NM, 1975.

[9] Cho, C., Murai, K., Suzuki, T., Suematsu, H., Jiang, W., and Yatsui, K.: “Enhancement of Energy Deposition in Pulsed Wire Discharge for Synthesis of Nanosized Powders,” *IEEE Transactions on Plasma Science,* **32**(5), 2004, pp. 2062-2067.

[10] Strand, O.F., Goosman, D.R., Martinez, C., Whitworth, T.L., and Kuhlow, W.W.: “Compact System for High-Speed Velocimetry Using Heterodyne Techniques,” *Review of Scientific Instruments*, **77**(8), 2006.

[11] Johnson, J.R., Taber, G., Vivek, A., Zhang, Y., Golowin, S., Banik, K., Fenton, G.K., and Daehn, G.S.: “Coupling Experiment and Simulation in Electromagnetic Forming Using Photon Doppler Velocimetry,” *Steel Res. Int.*, **80**(5), 2009, pp. 359–365.

[12] Webb, F.H., Chase, N., Ernstene, M., Tollestrup, A.V.: “Submicrosecond Wire Explosion Studies at Electro-Optical Systems, Inc.,” *Exploding Wires,* **1**, 1959, p. 33.

[13] Osher, J.E., Barnes, G., Chau, H.H., Lee, C., Speer, R., Weingart, R.C.: "Operating Characteristics and Modeling of the LLNL 100-kV Electric Gun," *IEEE Transactions on Plasma Science,* 17(3), 1989, pp. 392-402