Rapidly Vaporizing Conductors Used for Impulse Metalworking*

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Abstract

Forming, cutting and welding of metal by impulse has significant advantages, in that short time scales change the fundamental nature of the forming process and short duration impulses can be used with much lighter and more agile equipment because large static forces do not need to be resisted. Impulse forming is most commonly executed using electromagnetic forming. The application of electromagnetic forming is limited at high energies and large numbers of operations by the availability of long-lived electromagnetic coils (or actuators, as they are sometimes referred to). Low-cost, disposable actuators have been suggested as one method to treat this issue. Here we propose the use of low-cost foils or wires that are intentionally vaporized by a pulsed electric current to create an intense mechanical impulse. Here, a simple cutting and welding experiment is demonstrated as driven using a vaporized aluminum foil and further original experiments study the expansion of simple copper tubes using the impulse developed from copper and aluminum wires that are vaporized using capacitor bank discharge with nominal charged voltages between 3.4 kV and 6.7 kV, and peak currents between 60 kA and 150 kA delivered with rise times on the order of 20 µs. This gives some guidance on how forming operations may be designed and fruitful avenues for further research.

Keywords

Impulse forming, Bridgewire, PDV

1 Introduction

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Electromagnetic (EM) forming is currently, the most common method for impulse metalworking. However, the development of long-lasting actuators remains a problem. It is difficult to exceed peak pressures of about 350 MPa and generally the lifetime of actuators or forming coils decreases as the number of operations increases [1]. This is because the strength of the actuators depends on the mechanical, thermal and electrical properties of the coil and insulation materials. An example of this problem is shown in Figure 1 [2].

In this work, we propose a solution that may be appropriate for some applications. A high, short-duration current can vaporize the conductor it is carried through, and the formed gases and plasma may continue to dissipate energy as further current flows. This results in a very high-pressure region for a short period of time. Hence, if a work piece is kept near that conductor it will be accelerated to high velocity and useful work may be done on it. Here, tube expansion has been used as a model system for actuation using vaporizing wires. These simple experiments were done to evaluate the conditions for maximum efficiency of vaporizing metals in doing mechanical work. The arrangement is similar to that used by Fyfe et al. [3], except that in this case an incompressible medium is present between point of vaporization and tube. In former work, there was an air gap. Their work was more guided towards the study of shock waves generated from vaporizing metal. Here, more emphasis is on developing metal forming systems and the important required variables such as average pressure, optimal wire material, and charging parameters to maximize attainable pressure. These experiments have also been used to study the effects of the rate of current increase and perform a preliminary evaluation of the burst current density as an indicator of local pressure.

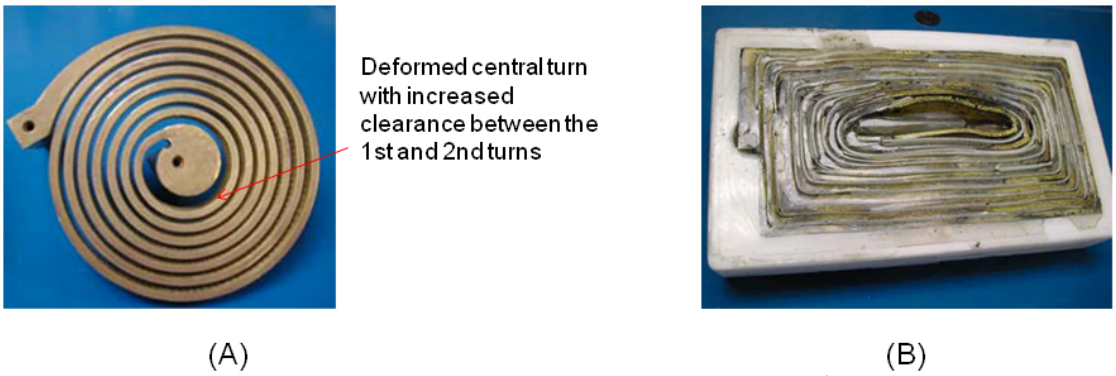

Figure 1. *(A) The spiral of a circular flat coil with deformed 1st and 2nd turn, (B) Coil fractured due to the deformation of the central turn [2]*

Before delving into detail, consider a simple example to show how an experiment using this technique can at once produce shearing, fast acceleration, and welding. The experiment is shown with explanation in the caption in Figure 2. A 10 mm diameter hole was sheared out from full-hard spring steel sheets at a nominal energy level of 4 kJ with an Al foil of thickness=0.002" (shown in Figure 2B). The velocity of the sheared flyer was measured using Photon Doppler Velocimetry (PDV) [4], which has earlier been used by Johnson et al [8] for measuring velocities during impulse forming operations. The velocity-time history of the flyer is shown in Figure 2D. As can be seen from the trace, the flyer undergoes very rapid acceleration once it shears from the sheet metal and reaches a peak velocity of ~375 m/s. It starts decreasing slightly after that probably because of air-resistance and friction against the wall of the die. When the sheared plug is made to impact a US quarter dollar held above shearing set up (shown in Figure 2C), the flyer not only shears a 10 mm hole in the quarter, but also welds with the impact surface of the quarter as shown in Figure 2 (F,G). This example is intended to demonstrate the versatility of this method as a means to work metal which may be extended to many other operations and geometries.

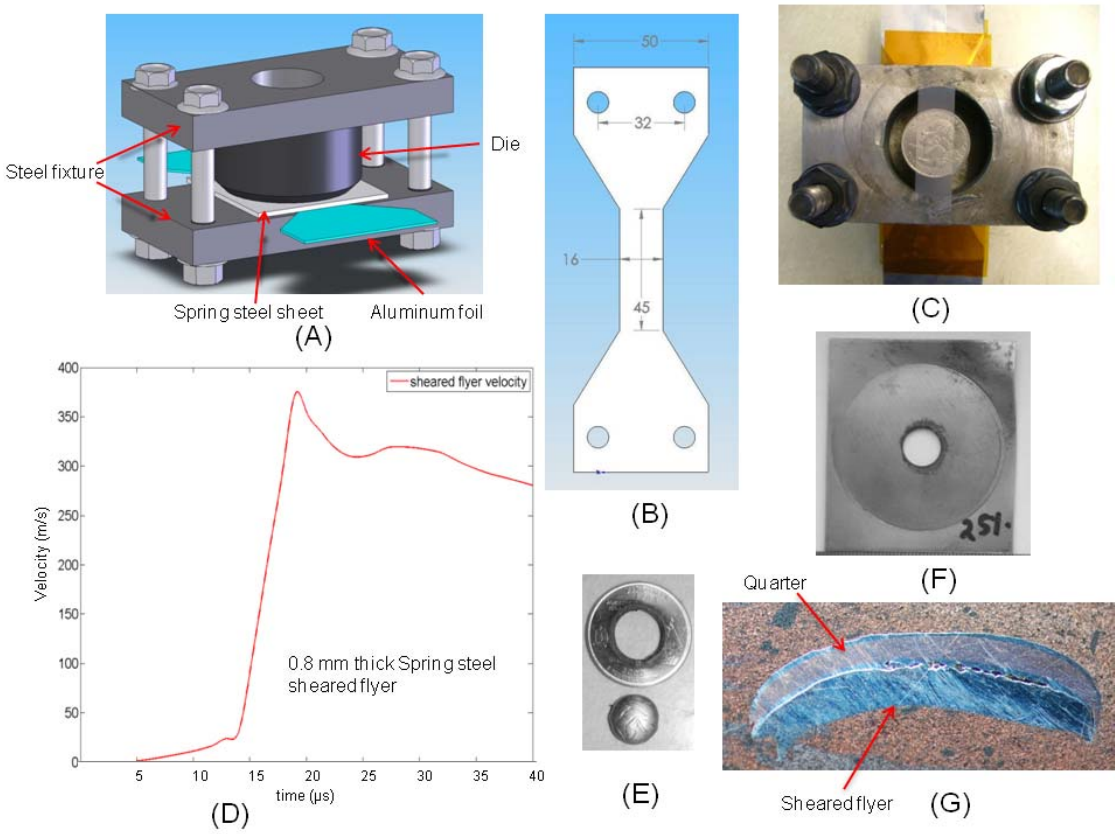

Figure 2: *(A) Schematic representation of the shearing set up, (B) Schematic of the dogbone shaped aluminum foil, (C) the top view of experimental set-up, (D) PDV trace of the sheared spring steel flyer showing a peak velocity of 375 m/s, (E) Sheared quarter dollar and the plug, (F) Sheared spring steel sheet, (G) cross-section of the quarter plug welded with the sheared flyer.*

2 Experimental Procedure

Tube expansion experiments were used as a model system to gain phenomenological understanding of vaporizing metal and to find the conditions for attaining the highest pressure to drive metallic workpieces. All the experiments are based on the simple circuit shown in Figure 3. A large amount of charge stored in a capacitor bank flows across a thin conductor, which can vaporize it. With rapid discharge from the capacitor bank, high currents can be developed before the wire vaporizes, storing some inductive and thermal energy [5,6]. This stored energy along with the gases produced by vaporization of conductor material and their subsequent reactions create a high pressure on the surrounding material.

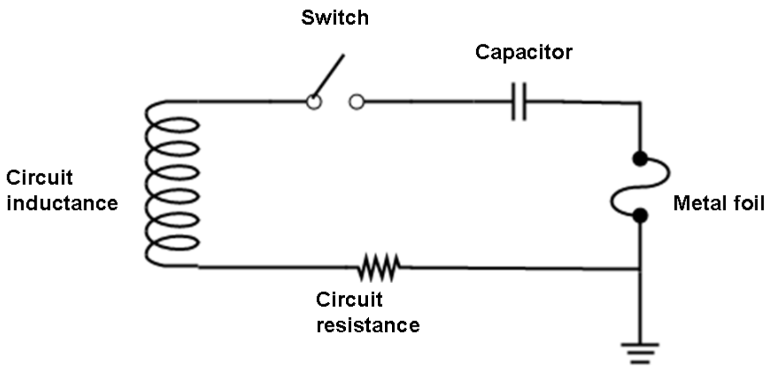

Figure 3. *Schematic drawing for rapidly vaporizing bridge-wire circuit.*

2.1 Capacitor banks

Two capacitor banks were used for charge storage. The first one (capacitor bank 1), is a commercial design from Maxwell-Magneform. It has a maximum capacity of 16 kJ at a maximum charging voltage of 8.66 kV. As will be seen later, only a fraction of the maximum energy was used in all the experiments. This unit has 8 capacitors, each triggered by two ignitron switches. This unit has a total capacitance of 426 μF and internal inductance of 100 nH and a primary circuit resistance of about 10 mΩ. This gives a rise time in shorted circuit of about 12 μs. All 8 capacitors were used in the circuit in these experiments.

The second capacitor bank (capacitor bank 2), developed at OSU has a maximum capacity of 24 kJ at a charging voltage of 10.9 kV. This unit has 4 capacitors divided into sets of two, which can be triggered separately using spark gap switches. In the present work, all of the capacitors were engaged in the circuit. Total capacitance of the unit is 404 μF, which is lower than the first bank. Inductance of capacitor bank 2 is 100 nH and its dynamic resistance is 4 mΩ. The short circuit rise time of this bank is 10 μs. However, a relatively high inductance connection was used to adapt the experiment to this capacitor bank, and gave a measured rise time of about 35 μs, much larger than that for the other system.

2.2 Experimental assembly

Copper alloy 122 tubes of 25.4 mm (1”) inner diameter, 28.57 mm (1.125”) outer diameter, and 76.2 (3”) length were annealed and quenched to provide a soft and uniform starting tube condition. This alloy is quite commonly used in plumbing pipe and tube, water and gasoline lines. A tensile test was conducted in the hoop direction of the tube and it was found that the yield strength of the material was 105 MPa while the ultimate tensile strength was 206 MPa. Uniform strain of 38% and total elongation to failure of 43% were also obtained. Corona dope was applied at the ends of the tube to prevent current shorting to the specimen. A durometer 80A urethane rod with diameter=25.4 mm (1”) and length=78.74 mm (3.1”) was inserted into the tube as shown in Figure 4. Aluminum and copper wires of diameter= 1.524 mm (0.06”) were inserted in a matching hole drilled through the center of the elastomer rod. The horizontal terminals of the capacitor bank are vertically aligned using a unique apparatus known as the FIRE (fully instrumented ring expansion), system developed by Johnson et al. [7].

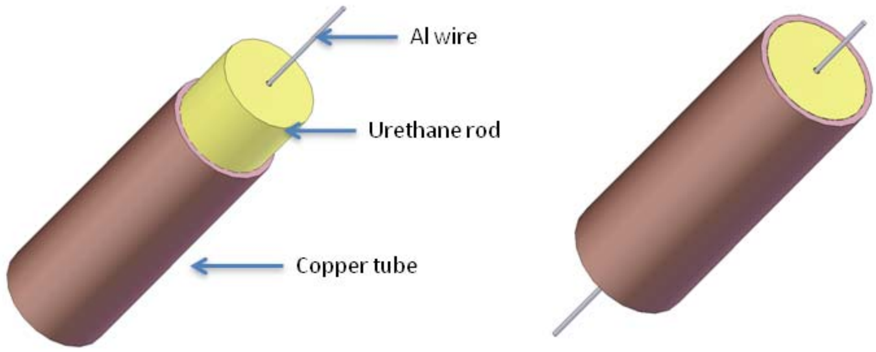

Figure 4. *Assembly of aluminum wire, elastomer and copper tube.*

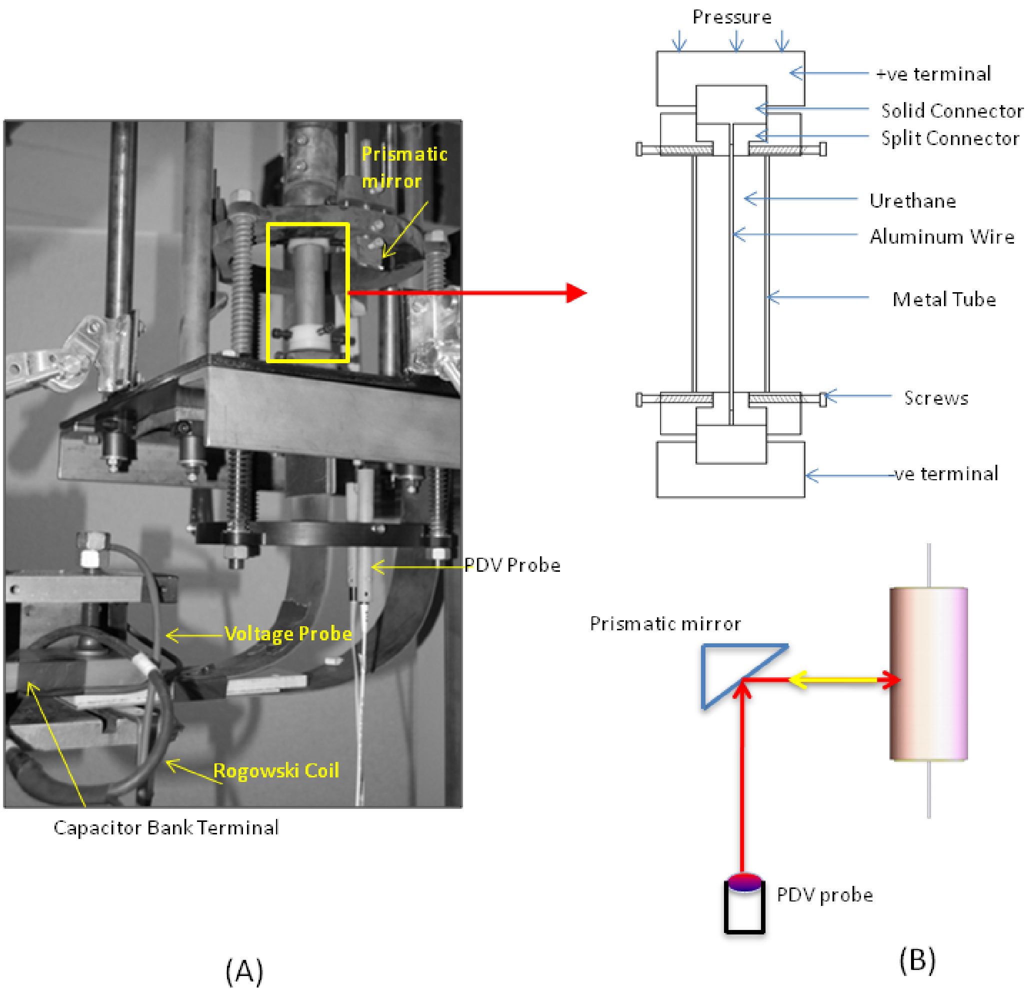

Figure 5. *(A) Actual experimental set up for instrumented tube expansion using vaporizing metal (B) schematics for the experimental setup and velocity measurement using PDV.*

2.3 Instrumentation and measurements

Current-time and voltage-time histories were recorded using a Rogowski probe and a 1000:1 voltage probe respectively in conjunction with an oscilloscope which acquires data at 5 Gs/s. Tube velocity was measured using the photon doppler velocimetry (PDV) technique recently developed by Strand et al. [4] with the OSU implementation described separately [8]

The probes were protected from direct impact by any tube fragments through using a periscopic adaptation as described in detail by Vivek et al. [9]. The schematic is shown in Figure 5(B). 2 PDV probes were directed towards the wall of the tube and were 120° apart from each other to assess expansion symmetry. The maximum diameter at the middle of the tube was measured using vernier calipers. A simple calculation can be done to estimate the sustained initial pressure on the inside wall of the tube. Based simply on using Newton's second law and ignoring the plastic resistance of the tube, the rate of acceleration can be equated to the pressure inside the tube as:

$$P = \frac{\rho \ddot{x}}{t} \tag{1}$$

where ρ is density, $\ddot{x}$ is the rate of acceleration and t is the tube thickness. The rate of acceleration can be easily estimated from the PDV data. In each experiment, efficiency is estimated which is the ratio of the maximum kinetic energy imparted to the tube and the electrical energy stored in the capacitor bank prior to discharge. The tube attains peak velocity before significant deformation occurs. This gives us a conservative estimate of efficiency, since initial potential energy is neglected.

To study the effect of current rise time on the efficiency, similar experiments were done on capacitor bank 2 at 9.6 kJ. Single-channel PDV was implemented along with current and voltage measurement. Experiments with copper wires were done on capacitor bank 1 and one-channel PDV was used.

3. Results

3.1 Aluminum wire

3.1.1 Capacitor bank 1

The specifics of the results from capacitor bank 1 are shown in Table 1. A sample trace for these experiments is shown in Figure 6. The final configuration of the tube is also inset in the figure. That experiment studied a tube that was expanded using an aluminum wire with a diameter of 1.524 mm at a 9.6 kJ energy level, the tube fractured as shown in Figure 6. At an input energy of 8 kJ the tube expanded without fracturing. The expansion was relatively uniform along the length of the tube, except at the ends that flared outward. The efficiency of this process has been calculated based on the conversion of input electrical energy into kinetic energy of the tube. This energy converts into potential energy, i.e. plastic work, during expansion of tube. The time period required for current to reach its peak value was in the range of 16-18 µs.

3.1.2 Capacitor bank 2

The second set of experiments yielded the results shown in Table 2. The peak velocity is in the range of 79-80 m/s while the final strain is in the range of 25-30%, which is fairly consistent. The current was also low as compared to those from capacitor bank 1; it reached its peak in approximately 35 µs.

3.2 Copper wire

With an 8 kJ discharge, the maximum strain was found to be 15.5%, while peak velocity during expansion was 32 m/s. There was no evidence of loss of energy by a current short through the tube. The experiment was repeated without velocimetry and the resulting strain was again very near 15%, a much lower value than is obtained with the aluminum wire, and the deformation was concentrated near the middle of the tube. Due to the low effective efficiency of the copper wire, most of the experiments were focused on aluminum wires and foils.

Energy level (kJ)	Rise time (µs)	Burst current (kAmps)	Final OD (mm)	%Strain	Peak velocities Channel 1 and 2 (m/s)	Efficiency (%)	Pressure (MPa)
9.6	17.2	143	42.9	50	123, 131	>6.7	282
8	18.8	131	40.6	42	112, 106	5.9	212
8	19.6	132	41.9	46	118, 112	6.5	225
6.4	20.4	120	36.1	26	90, 101	6	161
6.4	19.6	118	35.6	25	87	4.4	172

Table 1: *Summary of results for tube expansion using vaporizing metal on capacitor bank 1*

Energy level (kJ)	Rise time (µs)	Burst Current (kAmps)	Final OD (mm)	% strain	Peak Velocity	Efficiency (%)	Pressure (MPa)
9.6	35.8	52	36.8	29	80	2.5	154
9.6	35.8	53	36.5	28	79	2.4	152
9.6	37.9	52	35.8	25	-	-	

Table 2: *Summary of results for tube expansion using vaporizing metal on capacitor bank 2*

4. Discussion

There are some interesting observations which can be made based on these simple experiments. Firstly, it was shown that aluminum is a better bridgewire material than copper for this application. This can be attributed to the fact that gaseous aluminum is very reactive and readily forms oxides and nitrides. These reactions are highly exothermic leading to an increase in the temperature and pressure of the gases (i.e., the enthalpy for formation for alumina is about 1700 kJ/mol). Just to provide an estimate, if the aluminum bridgewire is fully converted to alumina (Al_2O_3), about 11 kJ of energy is released from this reaction. On the other hand, if a similar shaped copper foil is vaporized, just under 1 kJ of heat will be evolved from its conversion into oxides.

The 2-channel PDV (Figure 6) showed that the initial expansion of the tube was axisymmetric as the velocity-time traces of two points 120° apart overlaid quite well. However, when the first pulse of pressure is finished and the tube is expanding freely, a slight imbalance in initial velocities of different points, or perturbations, in the material can cause asymmetry of expansion. On an average, the expanded tubes were symmetric along the circumference. There were some end effects that caused flaring at the ends. The velocity traces have two or more local peaks. These peaks are the result of separate pressure impulses provided by the urethane rod. The first peak occurs due to the initial pressure impulse created by the burst of the wire. This impulse gets reflected off the wall of urethane rod and travels to a diametrically opposite point, leading to a second peak after some period of time.

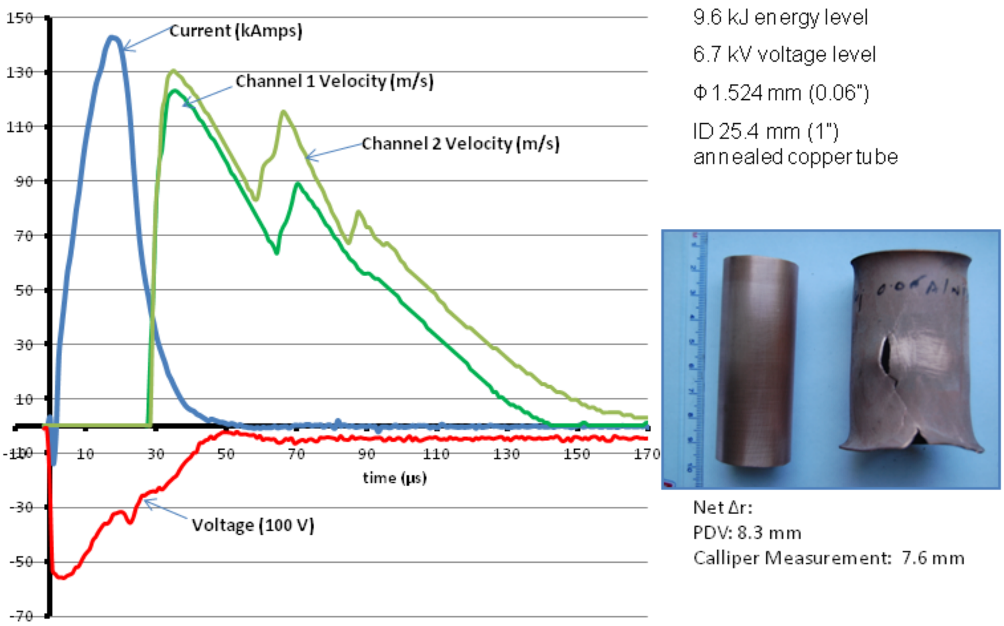

Figure 6. *Experimentally measured current, voltage and velocity during expansion of copper tube using electrical vaporization of 1.524 mm aluminum wire at 9.6 kJ input energy from capacitor bank 1. The jump in voltage (red curve) occurs at the instant when the wire vaporizes and its resistance increases suddenly, leading to excess voltage. On the right comparison of initial and final shape of the tube is shown.*

The pressure impulses remain for many microseconds and result in efficient transfer of energy into the tube. There may also be a shock wave that is much shorter in duration that is not detectable using this technique. Peak pressures up to 300 MPa were estimated based on this measurement method discussed in the procedure section. There are significant error bars, as shown in Figure 7. These are because of the uncertainty in determining when the tube starts to move. Although these pressures are significantly less than those reported in the past [5], it should be noted that these are driving pressures and not those generated upon impact with a target. These pressures are higher than flow and shear strength of many structural materials and can be used to form them at high speeds.

One of the main differences between this and previous work [5,6] is the current rise time, which in this study is in tens of microseconds as compared to a few microseconds in the other studies. With smaller rise time, more energy can be deposited into the wire before the instabilities start to set in. This leads to a higher burst current density. Hence the gases have more kinetic energy to create pressure on the surrounding material. The present work shows that this effect is true even for rise time in tens of microseconds. As shown in Figure 8, with 9.6 kJ input energy, experiments on capacitor bank 1 produced 50% strain while those on capacitor bank 2, which is slower, produced only 25 to 29% strain.

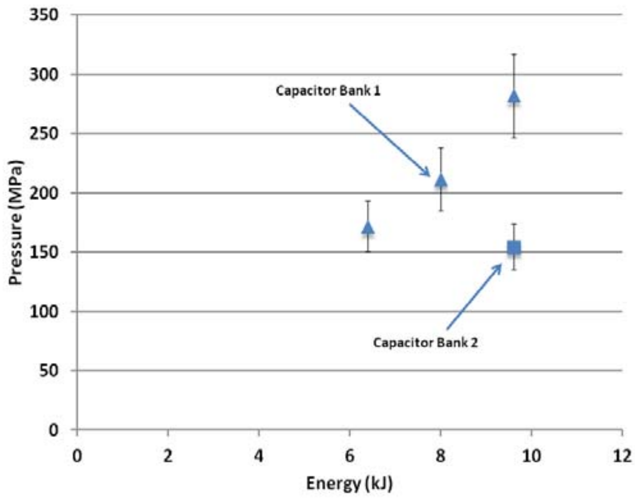

Figure 7. *Graph showing change in driving pressure with input energy. Triangular markers depict the data from capacitor bank 1 while those obtained from capacitor bank 2 are shown by square markers.*

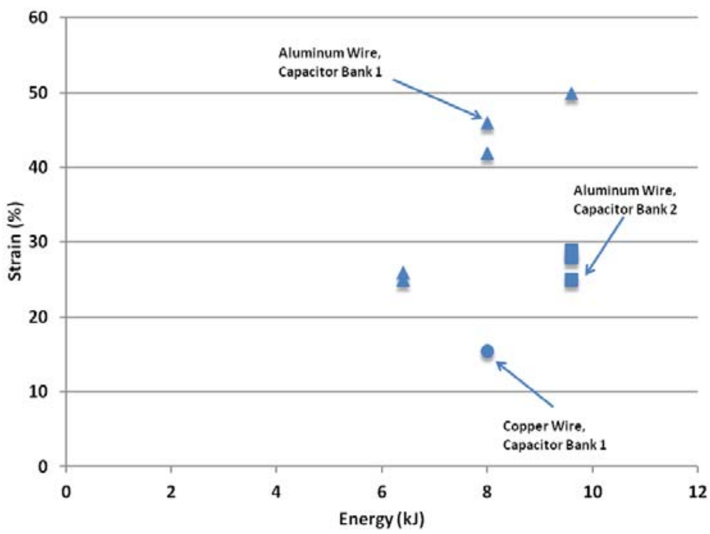

Figure 8. *Graph showing change in percentage strain with input energy. Triangular markers depict the data from capacitor bank 1 while those obtained from capacitor bank 2 are shown by square markers. Circular marker is the data from experiment with copper wire on bank 1.*

5. Conclusions

Fully instrumented experiments were carried out on the expansion of annealed 25.4 mm inner diameter, 28.6 mm outer diameter tubes of copper alloy 122 by electrically driven vaporization of coaxially placed metallic wires. Significant final deformations over a length of about 76.2 mm were obtained. About 50% and 30% increase in diameter were developed with discharges up to 9.6 kJ from separate capacitor banks. Aluminum, instead of copper was found to be the material of choice for wire. Efficiency of the process was not only dependent on the wire material, but also on the discharge characteristics supplied by the capacitor banks. It was found, that increasing the rate of increase of the current, the efficiency of the process can be increased. Although a good efficiency of about 7% was attained in the present work, faster capacitor banks which can be charged to higher voltage would make this process even more effective. Such capacitor banks are being developed at Ohio State University. From this work, it has been shown that vaporization of small metallic cross sections is an agile, repeatable, inexpensive, and efficient impulse metalworking technique. There is a clear need to develop a physics-based design science to support new manufacturing methods based on this technique.

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