Pressure heterogeneity in small displacement electrohydraulic forming processes

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Abstract

Electrohydraulic (submerged arc discharge) forming of sheet metal parts has been used as a specialized high speed forming method since the 1960's. The parts formed generally had a major dimension in the 5 to 25 cm range and required gross metal expansion in the centimeter range. In the descriptions of this process found in the literature, the pressure front emanating from the initial plasma generated by the arc is considered to be uniformly spherical in nature. At least one commercial system used this model to design hardware for pressure front focusing to optimize the forming process[1] and it has been the subject of continued research [2].

Recently, there has been commercial interest in adopting the electro-hydraulic method for the production of much smaller parts requiring very high die contact pressures but little gross sheet expansion. The forming of these small shallow parts required only a few kilojoules but proved to be problematic in other terms. The process development clearly showed indications of random patterns of large pressure heterogeneity across distances in the millimeter range. The apparent pressure heterogeneity produced unacceptable small scale variation in the part geometry.

A test program was designed to verify and quantify this effect using a target (die) consisting of a flat plate having small closely spaced holes. This 50 mm diameter target proved very effective in clearly showing the extent of the heterogeneity as well as the approximate local pressures. Various discharge energies were investigated along with different chamber shapes and pressure transfer mediums. The pressure heterogeneity across the target face was a common feature to all experiments. These test results indicate that a uniform pressure front model can be seriously in error for the electro-hydraulic process as implemented to date. The results of a qualitative hydro-code model of the test system including the discharge event are presented. The model results are similar enough to the experimental to imply that the coaxial electrode's inherent off center discharge is a primary suspect among potential explanations for the observed heterogeneity in terms of asymmetric shock interaction. The absence of this phenomena in the earlier electrohydraulic forming literature is also discussed.

Keywords

Forming, Pressure, Electro-hydraulic

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1 Introduction

High Speed Forming, (also referred to as High Rate Forming) of sheet metal parts has been in limited use by various industries since the 1960’s. The advantages of the different methods of High Speed forming are well know and published. The advantages include extended formability and high level of surface detail replication. In the United States, early electrohydraulic systems for High Speed Forming lost favour among the user community possibly due to the added complexity of the fluid medium of pressure transfer and or problems with inconsistent results. The simpler and cleaner Electromagnetic process of High Speed Forming became the dominate method especially for axisymmetric crimping and swaging. More recently, electromagnetic High Speed Forming has been demonstrated to be an effective means of generating larger parts, up to automotive body panel scale, of aluminium with difficult geometry [3,4]. A common characteristic of these aluminium parts is a large plastic deformation requirement, for which High Speed Forming has a known advantage. However, there is a large class of smaller parts that require only modest plastic deformation but a high level of small scale detail such as small radii and surface embossing. High Speed forming has known advantages for this class of parts also. Unfortunately, the less gross deformation required, the greater the need for a uniform pressure distribution generated by the system “actuator” method. In the electromagnetic process, traditional coil design can generate undesirable witness marks of the high pressure areas on the part immediately over the coil path. This coil image is not entirely washed out by subsequent plastic deformation as it would be for large deformation parts. A solution to this problem, called a uniform pressure actuator was developed by one of the authors at the Ohio State University [5]. The uniform pressure actuator however shares the major short coming of all electromagnetic driven High Speed Forming which is the requirement for a work piece of acceptable electrical conductivity. Many high value parts with small features and specific surface finish are also of materials of low conductivity such as stainless steel and titanium. The use of a high conductivity flyer plate (sheet) can be used to advantage for these parts but practically only for low production custom parts. This situation was a major impetus for a re-examining of a hydraulic method of High Speed Forming. These methods have no work piece conductivity requirements while being well capable of generating the requisite forming pressures. Pressure distributions were generally assumed to follow from an assumed spherical wave front generated by the expanding plasma bubble. This assumption has been shown useful in the general practice to date.

An electrohydraulic method for a manufacture process program for a small medical device made of a titanium alloy was considered a good application. It was during this process development effort, that the extreme pressure heterogeneity was identified [6]. Perhaps this is a rediscovery but a search of the available literature on electrohydraulic forming did not uncover any discussion of the phenomena. This paper presents the results of a short investigation to further illuminate the nature, origin and possible amelioration of the undesirable pressure heterogeneity.

2 Description of the test system and process.

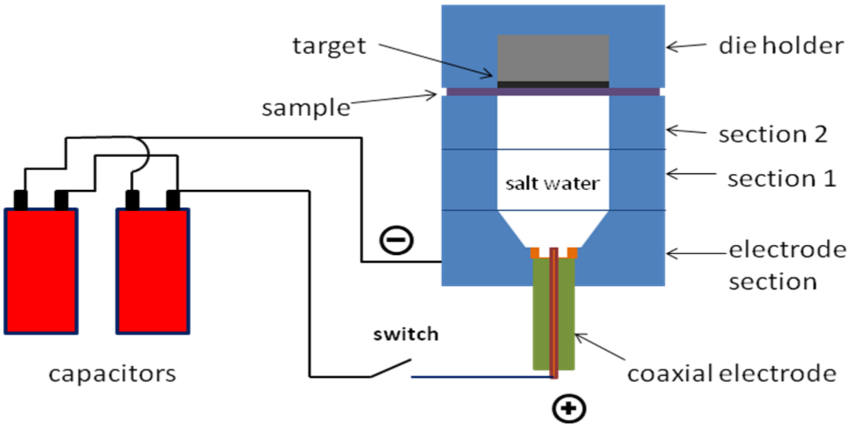
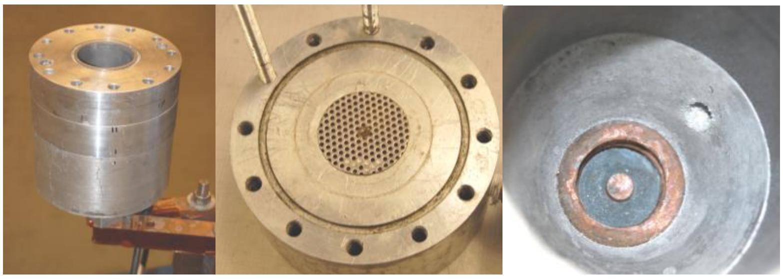


Figure 1: *Electrohydraulic test system schematic: chamber sections 1 & 2; 58mm inside diameter x 38mm long*



(a) (b) (c)

Figure 2: *The electro hydraulic test system , a) without target section, b) target section, c) coaxial electrode*

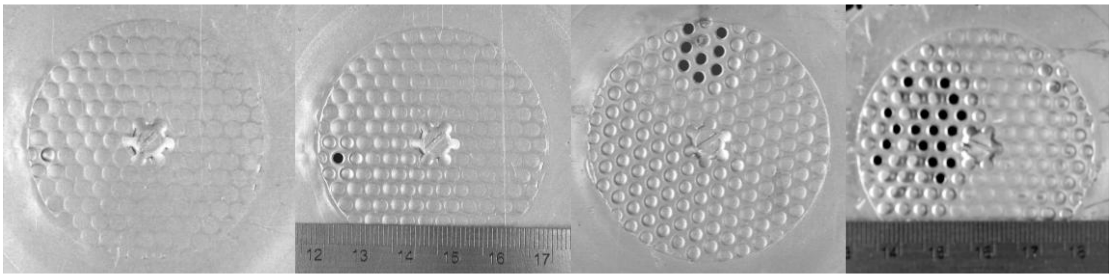
The coaxial electrode provided an arc length of 6.4mm which in the salt water medium reliably generated an arc at potential voltages of 5.0 kilovolt. The voltage was kept below 7 kilovolt for these experiments to minimize insulation breakdown problems. Note a coaxial electrode's arc is always off center. This was not initially considered an issue.

The target grid of Figure 2b is a piece of commercial perforated stainless steel sheet with 2.4 mm diameter holes on 3.8 mm centers. Not allowing deformation of the sample except at the grid holes proved to be a very inexpensive and effective means of recording the pressure distribution across the target face as can seen in Figure 3. The sample material is 6016-T4 , 1.0 mm thick aluminium sheet having an average yield strength of 123. MPa and an average ultimate strength of 223. MPa. The lower bound estimate of the pressure required to generate the hole can be found using equation (1) based on a simplified punch piercing relation from reference [7]

$$\text{Pressure} = P = S\pi Dt/(\pi D^2/4) = 4St/D \qquad (1)$$

Where: S= material shear strength t= material thickness, D=hole diameter

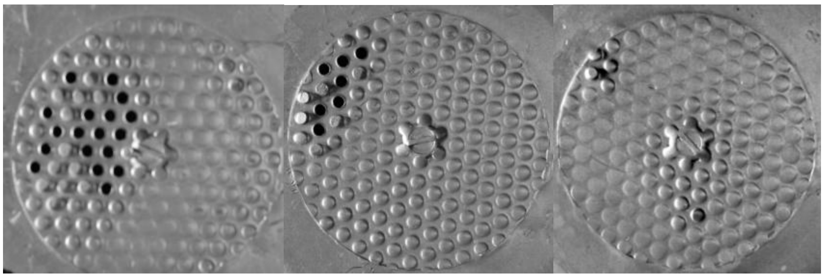
The minimum pressure at the sheared out grid holes, for the sample material, is given by eq. 1 as 227 MPa (33 ksI).



(a) (b) (c) (d)

Figure 3 Four test samples at four discharge energy levels a) 1.5 KJ(@120 μF), *b) 3 KJ(@120* μF), *c) 4.5 KJ(@120* μF), *d) 6 KJ(@240* μF),

Experiments were conducted at 1.5, 3.0, 4.5 and 6.0 KJ with bank capacitance of either 120 or 240 μF (one or two capacitors). The current-time traces followed the typical logarithmically damped sine function having a first half wave amplitude that varied from 40KA to 70KA with a rise time of 7-10 μsec. Experiments were also conducted using an insert which changed the conical volume of the electrode holder section into a 25 mm diameter right circular cylinder 25 mm long. Notable in Figure 3 is that the pressure distribution at 1.5 KJ had a lower peak pressure but not significantly more uniform than the higher discharge energies.



(a) (b) (c)

Figure 4: *Effect of chamber geometry change at constant 6KJ (@240* μF*) discharge; a) one spacer, b) two spacers, c) two spacers and electrode section, cone insert.*

Figure 4 qualitatively illustrates a pressure distribution variation with gross chamber geometry variation for a constant discharge energy. The basic variability of the pressure distribution for fixed process parameters is shown in Figure 5. All four samples resulted from 3KJ discharges using a two section chamber.

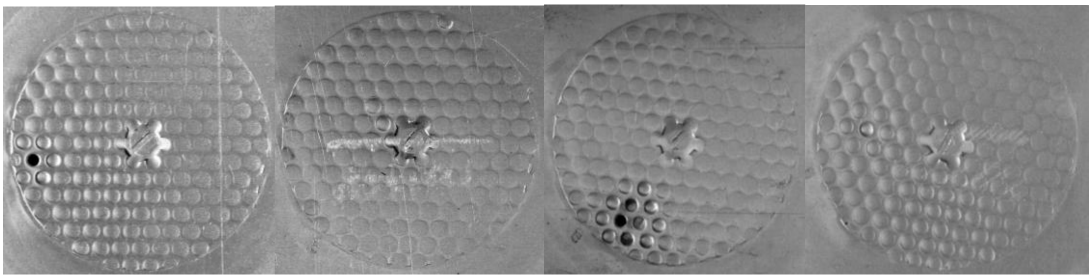
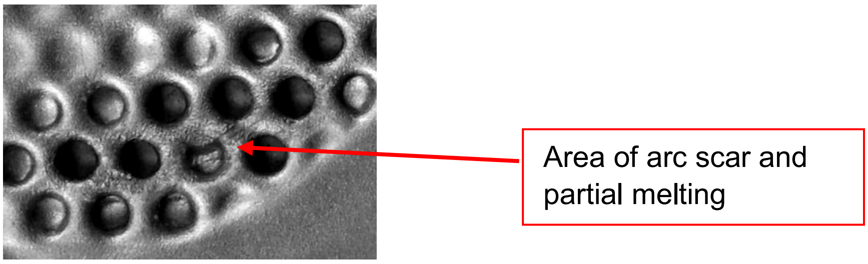


Figure 5: *Samples from four experiments using 3 KJ (@120* μF) *discharge energy in the two section chamber*

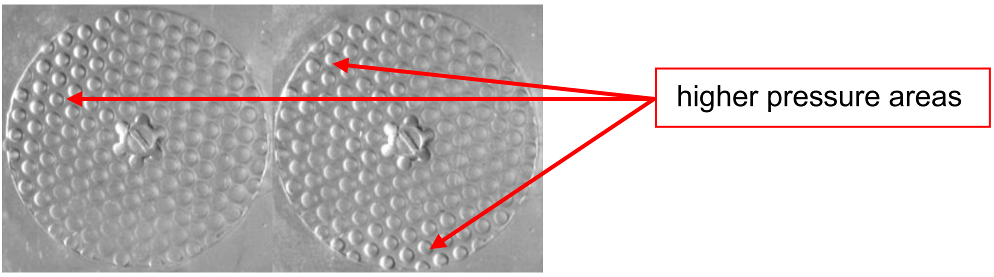
Figure 5 indicates that pressure “hot spots” can occur in a seemingly random manner under seemingly constant process parameters. Comparing Figure 5 with Figure 4 reveals that the extent of the “hot spot” generally increases with discharge energy. However, the localized nature, seen in the abrupt change from slight dimpling to shear-out, is evident at 3 and 6 KJ discharge levels. The experimental results of Figures 3 to 5 are consistent with those for the medical device component process reported in reference [6].
In addition, reference [6] provided evidence of an arc streamer from the electrode to the sample which was also seen in the experiments of this paper as shown in Figure 6.



Area of arc scar and partial melting

Figure 6: *Evidence of arc streamer contact with sample*

A 25mm thick natural rubber plug was placed in the chamber such that it contacted the sample. The plug was closely fit to the chamber internal diameter but not otherwise constrained. The plug served to eliminate the very high pressure localizations but did not entirely eliminate the observable asymmetric pressure variations as seen in Figure 7



higher pressure areas

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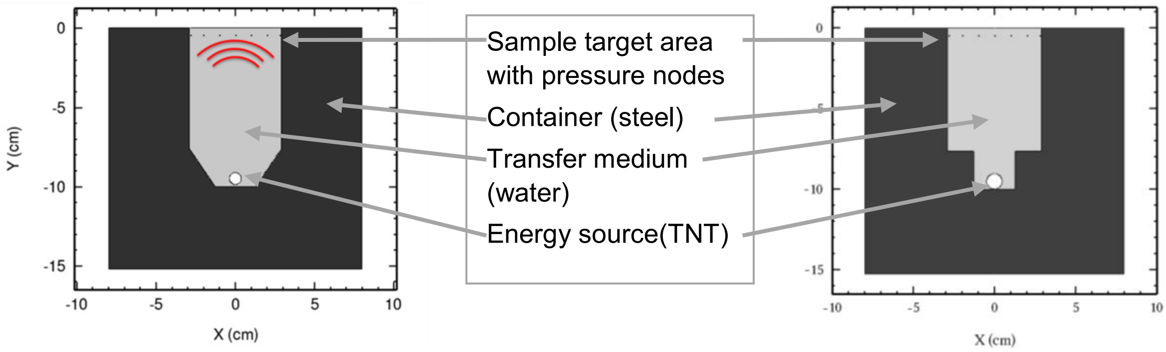
Figure 7: *Two samples subjected to 6 KJ(@240* μF*) discharge with an intervening 25 mm thick natural rubber pad.*

The nature and pattern of the pressure heterogeneity displayed in the results of theses experiments and those reported in reference [6] are certainly consistent with well known effects of the interactions of reflected shock waves. A simple numerical model of the test apparatus was used to investigate the influence of chamber geometry and the radial location of the discharge event in relation to the central axis of the chamber.

3 Numeric model of the experimental system

The model employed a multi-material, large deformation, strong shock wave, solid mechanics code called CTH, developed at Sandia National Laboratories. CTH has models for multiphase, elastic-viscoplastic, porous, and explosive materials. CTH numerically solves the partial differential equations describing the conservation of mass, momentum, and energy. It does this in a structured Eulerian mesh fixed in space and uses equations of state (EOS) to close the coupled system of equations. CTH is capable of predicting cavitation in fluids as the result of events such as the submerged arc discharges of the experiments presented in this paper.

3.1 Numerical Model Geometry



(a) (b)

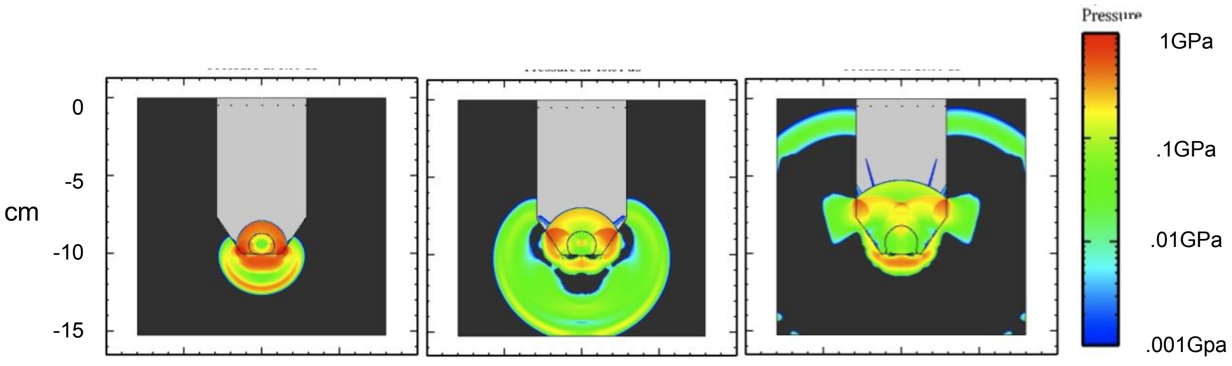
Figure 8: *Schematic of the CTH model geometries and component materials, (a) original, (b) with electrode section insert*

For simplicity, the energy source was modelled as a small mass of TNT that would release about 3 KJ of energy when ignited. The main difference between an explosive shock pulse and the electrically generated shock is the shape and duration of the generated pulse. The explosive completes its detonation burn within ~1.0 µsec. compared to the average electric arc pulse rise time of 8.5 µsec. The model input was about 3/4 of a gram of TNT which has an energy density of 4184 J/g. Compared to the arc discharge the explosive will generate a less dispersive shock wave. A higher amplitude, but shorter duration shock providing the same energy input is generated. The intent of the explosive is to provide a shock in lieu of an electric spark. The shock structure will be different and this difference has effects on the target end, but is useful in a qualitative sense. The main focus is to illustrate how the shocks interact within the structure in terms of qualitative effects not quantitative levels or values.

Two chamber geometries were modelled. The original two section chamber shown in Figures 1 and 8a and a second where the truncated cone volume at the electrode bottom end was replaced by a simple cylindrical volume of the same diameter as the electrode (~ 25mm), Figure 8b. Each geometry was run with two discharge location inputs. One at the bottom center of the chamber and another with the discharge off center by 6 mm. The charge offset represented the nominal center location of an arc generated in the annulus gap of the coaxial electrode shown in Figure 2c. The centered discharge case was run as a 2D axisymmetric model whereas the offset discharge case required a full 3D model.

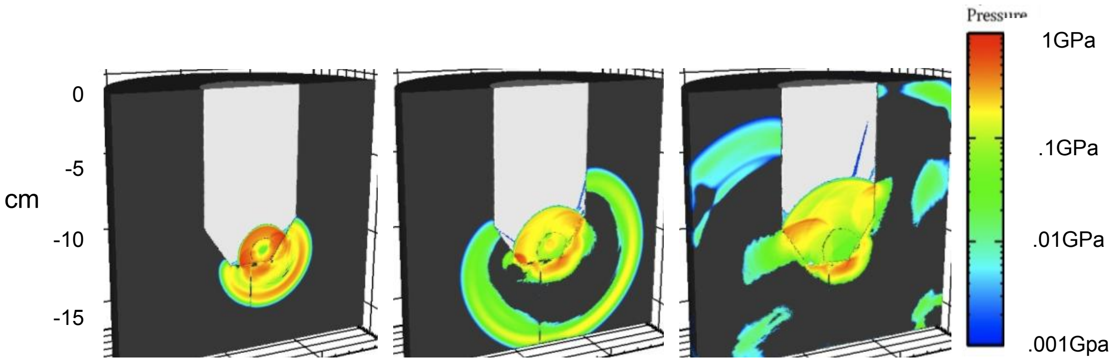
3.2 Numerical model results

Graphical results of the CTH model solutions are presented in Figures 9, 10 and 11 Comparison of Figure 9 with Figure 10 clearly shows a significant pressure distribution asymmetry due to the 6mm offset of the discharge event.



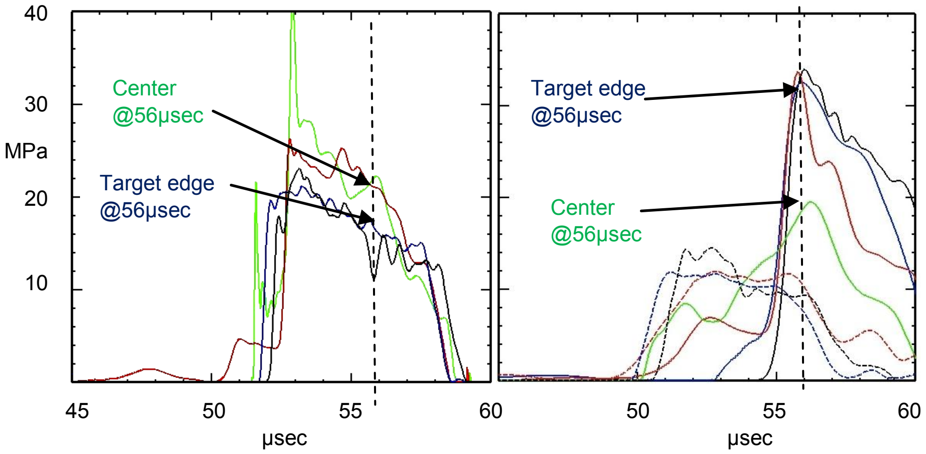
(a) (b) (c)

Figure 9: *Pressure – time history for symmetric case ; a) 5 µsec, b) 10 µsec c) 20 µsec*



(a) (b) (c)

Figure 10: *Pressure – time history for asymmetric case ; a) 5 µsec, b) 10 µsec c) 20 µsec*

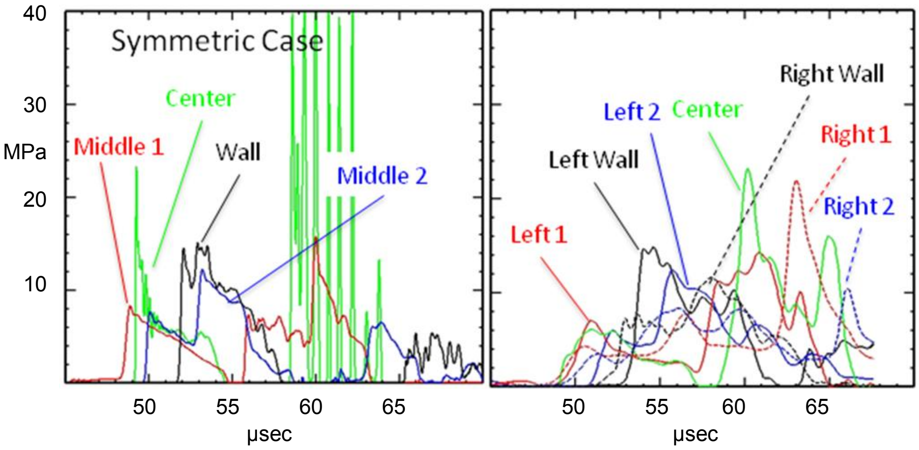


(a) (b)

Figure 11: *Pressure-time histories at the model tracer nodes, a) symmetric case, b)asymmetric case*

The second model geometry simulated the effect of the straight cylindrical volume at the electrode end of the chamber. The simulation results are presented in Figure 12. Inspection of the graphs in the figure reveals a generally lower and more uniform pressure distribution for the asymmetric discharge in comparison to the original chamber geometry. The higher pressures change sides during the asymmetric shock impingement event

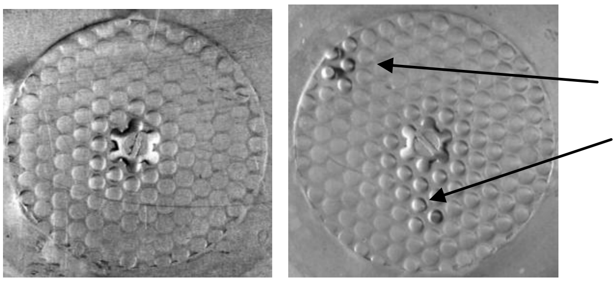
(Figure 12b). The left side pressures being greater than the right side up to 55µsec and the right hand node pressures are considerably greater than the left side beyond 60µsec. Figure 12a, the symmetric case displays a series of high pressure spikes at the center node at 60µsec which are considered to be cavitations. No evidence of cavitations was seen in the asymmetric simulations or in the experiment samples.



(a) (b)

Figure 12: *Pressure-time histories at the model tracer nodes in the second chamber geometry, a) symmetric case, b)asymmetric case*

The two samples shown in Figure 13 were generated at 4.5 and 6 KJ using the chamber geometry described by Figure 8b e.g. two chamber sections and a cylindrical volume at the electrode.



Small pressure hot spots approximately at the 2nd middle and first middle simulation pressure tracer node

(a) (b)

Figure 13: *Two samples generated using Figure 8b chamber geometry using a) 4.5KJ (@120* µF) *discharge and b) 6 KJ (@240*µF) *discharge.*

Figure 13 appears to corroborate the results of the simulation of the second chamber geometry. With the exception of the small hotspots, the pressure distribution is more uniform than for the 6KJ samples from the original geometry chamber which is also consistent with the simulation results. Whether this agreement would be maintained for a larger sample size is an unanswered question in this investigation.

4 Summary and Conclusions

This investigation into extreme pressure heterogeneity in electrohydraulic pulse forming replicated the results described in Reference [6]. Specifically areas of a 50 mm diameter sample experienced pressures in excess of that required to shear out the 2.4 mm target grid holes (>230 Mpa) while adjacent areas, a millimetre or two away experiences pressures sufficient only to raise a slight bump at the target grid holes. This effect, to a greater or lesser degree, persisted over a span of discharge energy levels from 1.5 to 6 KJ and for chamber depths of 25, 63 and 100 mm.
The introduction of a 25mm thick natural rubber plug attenuated the heterogeneity considerably. Similar results were obtained by changing the chamber geometry at the electrode from a truncated cone diffuser geometry to a cylinder of the same height and a diameter just sufficient to accommodate the coaxial electrode.

A simplified numerical model of the experiment was built using the CTH code from Lawrence Livermore Labs with the intent of obtaining qualitative insights into the prime cause of the pressure heterogeneity. The results from the simulations were qualitatively consistent with the experimental results. From the simulation output it was seen that the original geometry was quite sensitive to off center discharges in terms of generating heterogeneous pressure distributions. The main culprit in the process appears to be the coaxial design of the electrode. Coaxial electrodes are sturdy and have good erosion properties but can not practically generate a centered discharge. Experiments and simulation results using the smaller cylindrical discharge volume at the electrode end of the chamber indicate that a extended variation of this geometry having a greater aspect ratio may be effective in reducing the pressure heterogeneity to acceptable levels. The other alternative is, of course, to design an electrode system that can reliably generate the discharge arc at the center line of the chamber without disturbing/occluding the initial arc plasma bubble. It may also prove productive to seek both chamber and electrode designs that can produce an appropriately uniform pressure front at the work piece. Additional changes to the system, which were not investigated were degasification of the water and inverting the chamber. Electrohydraulic systems with the fluid and electrode above the work piece has been utilized without reports of the pressure heterogeneity described in this paper. However, the complex nature of the shock wave nucleation and interaction with reflections from the chamber geometry should be acknowledged in all cases. These shock interactions clearly may render a system utilizing only fluid as the pressure transfer medium inherently too heterogeneous in terms of target pressure distribution unless large plastic deformation is the goal. For parts requiring only modest plastic deformation but high definition, a system wherein any pressure heterogeneity is absorbed and smoothed by an intervening elastomeric since that material does support cavitations. The experimental results shown in Figure 7 using the natural rubber insert provide evidence that this may be another productive approach.

The principal impetus behind this investigation is the desire to harness the advantages of high speed forming for materials ill suited to electromagnetic methods utilizing the main component of electromagnetic forming; the capacitor bank. The electrohydraulic approach used in these experiments and those of [6] have the potential advantages of relative low cost, compactness and shared capital equipment with electromagnetic methods. However, the observed extreme pressure heterogeneities reported in this paper will need to be controlled or eliminated before the method can be productively applied to the targeted class of parts. e.g. high definition, low gross deformation parts of low electrical conductivity. That the results reported here are not explicitly available in the previous literature on high speed, electrohydraulic forming can be attributed to the simple fact that large plastic deformation was the goal of the early work. Large deformation would tend to obliterate any initial pressure heterogeneity especial after die contact.

5 References

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