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Vaporizing foil actuator used for impulse forming and embossing of titanium and aluminum alloys

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ABSTRACT

Electrically driven rapid vaporization of thin conductors is known to produce short-duration pressure pulses of high magnitude. This impulse can be used for applications such as high strain rate forming, shearing, collision welding, and springback calibration. Mechanical impulse was developed from aluminum foils of various thicknesses, which were vaporized using a capacitor bank discharge with a maximum charging voltage of 8.6 kV. Peak current was delivered on the order of 100 kA with rise times of about 12 μs. In this work, polyurethane was used as a medium to transfer pressure from the aluminum foil vaporization zone to the workpiece. Fundamental experiments, where AA 3003-H14 aluminum alloy was formed into perforated plates, show that for a given foil thickness, a limit existed over which supplying higher electrical energy from a given capacitor bank did not necessarily result in higher pressure. The magnitude of generated pressure was proportional to the excess Joule heat deposited into the foil before it burst. Although the polyurethane layer helped spread the pressure pulse over a larger area, the resulting pressure distribution remained heterogeneous. Practical applications, such as forming into cavities and embossing into shallow dies, were possible with this method. Sheets of 0.508 mm thick commercially pure titanium were nearly fully formed into a cellphone case die using a hybrid process that combined a quasistatic pre-forming step with a vaporizing foil forming step. Sheets of 0.508 mm thick AA 2024-T3 aluminum alloy were embossed into a die with features of varying depths. Aluminum foils with straight and curved active sections were used as actuators. The curved-section foils resulted in higher conformation of the workpiece to the die in the center region, while the straight-section foils produced better conformity to the die features on the ends.

1. Introduction

Passage of an electrical current of large magnitude through a thin conductor can cause its rapid vaporization. The rapid expansion of the gases creates a high-pressure pulse. Generally the discharge source is a capacitor bank and the conductor is in the form of a thin wire or foil. “Exploding” conductors have been studied before, but the emphasis has mainly been on understanding the phenomenon itself or its application in shock physics and explosive detonation. Several studies were performed that utilized rapid vaporization of metal foils to achieve high velocities in flyer plates. Keller and Penning (1962) achieved 4–5 km/s velocities in thin dielectric flyers that were impacted with target plates. The impact results revealed shock properties of the dielectric and the target plates between 1 and 10 GPa. Stroud (1976) later produced 100 GPa pressures with an improved method and used the resulting shock pressure as a detonation source for explosives. Even greater pressures, upward of 500 GPa, were then reached by Chau et al. (1980) through use of a thin metal layer attached to the dielectric plate. This improved results in two key ways. Additional driving force was created due to the momentary repulsion between the magnetic field of the foil and the conductive metal workpiece layer, which increased with increasing applied electrical current. The material properties of the layer itself were also important, because although it resulted in increased mass, it offered greater shock impedance, resulting in overall higher impact pressures. These improvements produced parallel flyer motion for the first 5 mm of travel and resulted in velocities near 20 km/s. This method was used to characterize shock detonation of explosive materials, but much greater range than before was possible, as detonation pressures up to 28 GPa were attained. Other applications, such as quick action fuses, discharge pulse sharpening, and nanopowder manufacturing, have also been explored in the past.

Use of rapid metal vaporization in the metal working industry has been limited. Electrohydraulic forming (EHF) is implemented by underwater electrical detonation of bridgewires or, more commonly, by high voltage dielectric breakdown across spark gaps. As early as 1961, electrohydraulic forming was researched for use in

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metal deformation, as Felts (1961) first demonstrated how pressure impulses large enough to form sheet metal could be produced with this method. The underwater current discharge was successfully used to form metal objects into parts of relatively small structural mass. Woetzel et al. (2006) demonstrated that experiments which used aluminum wires as a chemically reactive detonation source produced comparable deformation to those initiated with secondary explosives, such as PETN. Daehn (2006) commented that this forming method has so far been difficult to commercialize, but that some organizations still successfully use this type of process for formation of small batches of parts. Golovashchenko (2010a) demonstrated the use of pulsed electrohydraulic discharges for calibration of a partially formed metal part onto the forming surface of a die. In a related work, Golovashchenko (2010b) used underwater electric discharge for high speed trimming of metallic blanks, with discharge energies ranging from 5 kJ to 50 kJ.

Since then, Vohnout et al. (2010) conducted experiments to determine that the water used in the EHF process should be free of impurities and gases to prevent any unwanted cavitation during detonation. Cavitation can cause non-uniformity in pressure distribution and reduce overall efficiency if it is not avoided. For that reason, Vivek et al. (2013a) replaced water with polyurethane as a pressure transfer medium. Polyurethane was chosen because it maintains a high Poisson's ratio (thus low compressibility) at pressures ranging up to 4.2 GPa (Kanel et al. (2004)). That work was focused around fundamental studies via instrumented tube expansion experiments. In more recent work, however, flat sheets of polyurethane were used to transfer the pressure to the workpiece. Additionally, thin foils were used as actuators instead of wires so that a planar pressure pulse could be produced for forming flat sheets. Vivek et al. (2013b) demonstrated the use of these vaporizing foil actuators without the urethane pad to implement collision welding of dissimilar metals at much smaller scales than explosive welding.

According to Thiruvarudchelvan (1993), use of a polyurethane pad for pressure transfer during forming operations introduces multiple advantages, such as elimination of alignment and mismatch problems, minimization of springback, and accommodation for thickness variations. Additionally, the same flexible pad can be used for forming into different shaped dies. Lubrication is often unnecessary, and the workpiece surface in contact with the polyurethane pad is unharmed. Some disadvantages of using polyurethane, including higher press capacity, possibility of wrinkling, and shorter working life, are also considered in comparison to corresponding tools used in conventional forming processes. A more recent paper by Thiruvarudchelvan (2002) gives an account of different configurations in which urethane pads are currently being used for forming applications.

This article has been divided into two main parts: (1) fundamental studies focused on understanding the effect of foil thickness on efficiency of pressure pulse generation and magnitude of forming, (2) application of the technology to practical use, such as forming of a depression and embossing. Procedures, results, and discussions are presented together for each section. At the end, a summary of results and key lessons from this work have been discussed.

2. Parametric studies

Tube expansion experiments described by Vivek et al. (2013a,b) showed that, if end effects are ignored, use of the rapid metal vaporization technique can result in uniform axisymmetric deformation over a length of 76.2 mm. This can be ensured if the frequency of the discharge source is high enough and the diameter of the wire is uniform. Applying the same technique in a flat configuration, however, is a challenge. In the present work it will be shown how vaporizing a thin aluminum foil under a constrained elastomer sheet can create relatively uniform pressures over an area larger than the foil itself.

2.1. Methods for indirect pressure estimation

During impulse forming operation, because the pressure pulse lasts for a very short duration, its measurement requires sensitive gauges with low response times. There are some methods by which pressure can be estimated indirectly as well. Feature heights on resultant workpieces from extruding or punching through a perforated plate and those from impression die embossing can be used to estimate the range of pressure during those operations. While sensors are good for finding the temporal history of the pressure pulse, the spatial distribution can be more easily investigated by examining the resultant workpieces from pressure estimation experiments.

2.1.1. Bulging into a perforated plate

Bulging of a sheet metal workpiece into a perforated steel plate is often used as a technique for indirect measurement of the magnitude and distribution of pressure in explosive forming (Rinehart and Pearson, 1963) and electrohydraulic forming (Knyazyev et al., 2010). The height of each formed hemispherical dimple is inversely proportional to its radius of curvature. By modeling each dimple as a thin-walled pressure vessel, the amount of pressure created at each location can be estimated, according to Laplace relation for spherical shells in Eq. (1):

$$\sigma = \frac{P \times r}{2t} \tag{1}$$

Assuming constant flow strength, σ, as larger pressures, P, are exerted at different locations, the radius, r, will be driven to smaller values, thus resulting in dimples of different curvatures, and ultimately different heights. Because the material continues to form into the perforation until the generated pressure balances the flow strength of the material, it is inversely proportional to the radius of curvature, hence directly proportional to the height of the dimple. Therefore, the height of a dimple is directly proportional to the pressure experienced by that area of the sheet metal. This is a simplistic model which works on the assumption that the thickness of the sheet metal is much smaller than the radius of the dimple, which is not the case here. SanJose et al. (2012) provide a more detailed analytical model for pressure estimation based on this method. Important factors such as cavitation time and transition from elastic to plastic deformation are also considered by Rinehart and Pearson (1963).

2.1.2. Punch out

During the extrusion of the workpiece into a perforated plate, it is also possible that the dimple gets punched out before it reaches its maximum height. The pressure required to punch out a circle of radius r from a sheet of thickness t, and shear strength τ, can be estimated from Eq. (2).

$$P = \frac{\tau \times 2t}{r} \tag{2}$$

Since shear strength, τ, is generally less than the flow strength, σ, of a material, it can be expected that a dimple will almost always punch out before it can form into a hemisphere. Therefore, if the dimple is punched out, then the minimum pressure can be estimated with Eq. (2), otherwise it can be estimated by Eq. (1) which takes into consideration the dimple height.

2.1.3. Coining

Monaghan (1988) provides an upper bound analysis of the pressure required during the coining stage of a closed die axisymmetric