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Electrically driven plasma via vaporization of metallic conductors: A tool for impulse metal working

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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 enable 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. However, 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 counteract this issue. Here we propose the use of low-cost foils or wires that are intentionally vaporized by a pulsed electric current, in order to create an intense mechanical impulse. Applications including cutting, forming, and dimensional calibration are demonstrated and discussed. The available literature that could provide design guidance is reviewed. A simple cutting and welding experiment using a vaporizing aluminum foil is demonstrated. Further 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 and 6.7 kV, and peak currents between 60 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, opens possible areas for further research.

1. Introduction

There is interest in impulse metalworking due to several advantages it offers as compared to a corresponding quasi-static process. Increased forming limits, reduced springback, low cost tooling and reduced wrinkling are some of the documented advantages of impact forming (Psyk et al., 2011; Daehn, 2006). Shearing at high speeds has been shown to reduce sliver formation and provide increased dimensional tolerance (Breitling, 1998). There is also a critical velocity above which shearing requires much less energy because of localized deformation along narrow adiabatic shear bands (Klepaczko and Klosak, 1999). Impact welding is a solid state process that allows the joining of dissimilar metals with little to no heat affected zone (Brown et al., 1978). A common observation in impact welding has been that the weld zone is stronger than the parent material (Zhang et al., 2010). All these factors warrant a concerted effort toward developing impulse metalworking into a mainstream manufacturing technique. The International Impulse Forming Group (I^2FG: *www.i2fg.org*) has recently been established to facilitate knowledge sharing and infrastructure development.

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 at high pressures (Daehn, 2006). In this work, a solution that may be appropriate for some applications is proposed. A high, short-duration current can vaporize a conductor it is carried through, and the formed gases and plasma may continue to expand by energy deposition due to the continued electrical current. 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. This vaporizing conductor can represent a low-cost, efficient and robust disposable actuator used for impulse metalworking. This method can be used for cutting, forming, embossing, and springback calibration and is ideal for low volume production.

Before delving into detail, we present 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 Fig. 1. A 10 mm diameter hole was sheared out from full-hard spring steel sheet at a nominal energy level of 4 kJ with an Al foil with a thickness of 0.051 mm, shown in Fig. 1(C). The velocity of the sheared flyer was measured using Photon Doppler Velocimetry (PDV), the implementation of which has

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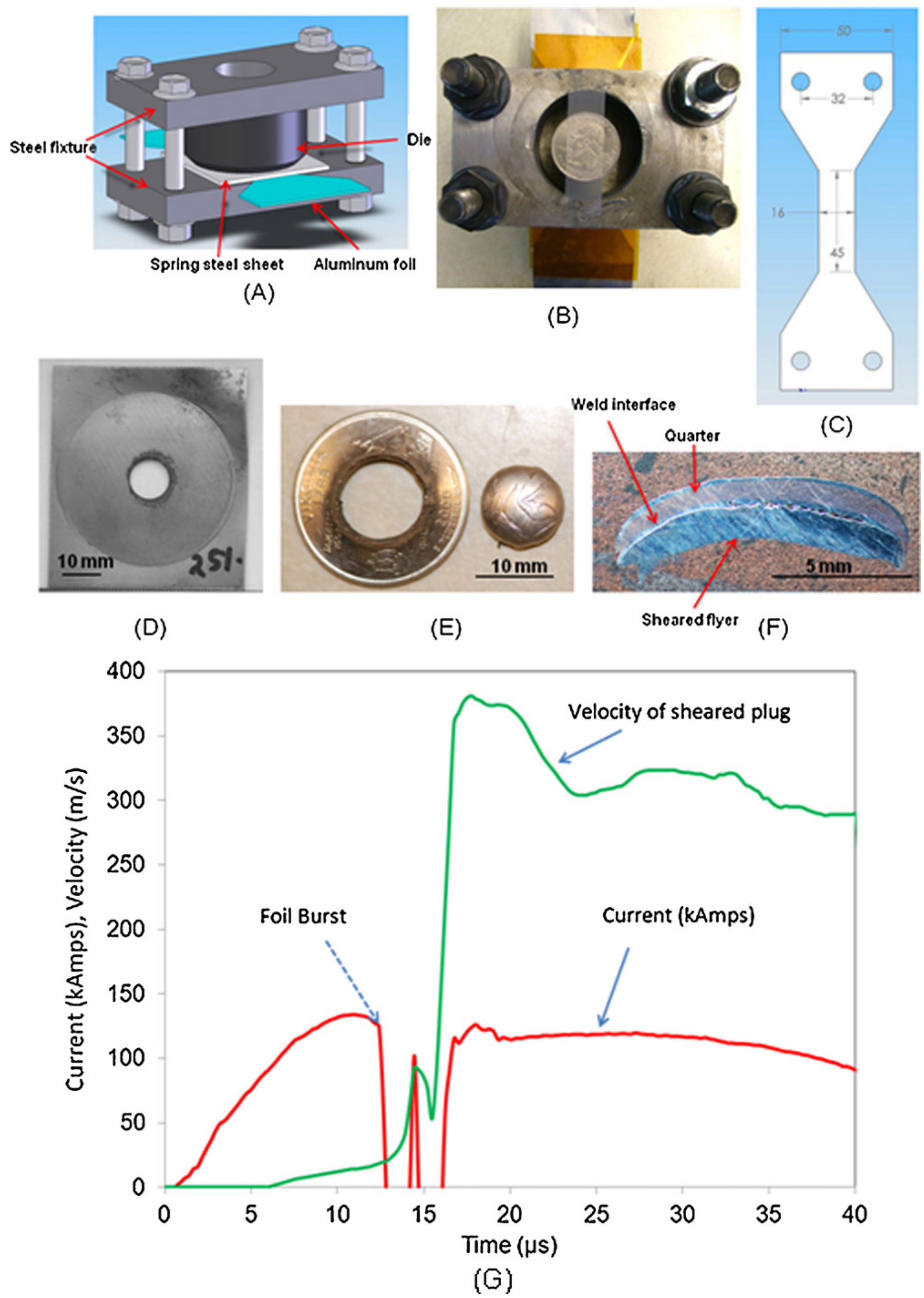

Fig. 1. (A) Schematic representation of the shearing set-up, (B) the top view of experimental set-up, (C) schematic of the dogbone shaped aluminum foil, (D) sheared spring steel sheet, (E) sheared quarter dollar and the plug welded with sheared flyer (hidden below the quarter), (F) cross-section of the collision weld between sheared flyer and the quarter plug, (G) PDV trace of the sheared spring steel flyer showing a peak velocity of 375 m/s.

been described by Johnson et al. (2009). The velocity–time history of the flyer is shown in Fig. 1(G). 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 decelerating slightly after that, most likely due to air-resistance and friction against the wall of the die. When the sheared plug is made to impact a US quarter dollar coin held above shearing die by cellophane tape as shown in Fig. 1(B), 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 Fig. 1(E and F). Further details of shearing experiments are given later, but 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.

This article is presented in two parts: (1) fundamental studies based on tube expansion that provide some physical expectations from the process, and (2) applications, where springback control and shearing are emphasized. Application of this technique to other metal processing applications such as collision welding and embossing in later publications will be discussed in later publications. 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 set-up was similar to that used by Fyfe and Ensminger (1964), except that in this case an incompressible medium is present between point of explosion and tube, whereas Fyfe's work contained an air gap. Their work