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# Uniform Pressure Electromagnetic Actuator – An innovative tool for magnetic pulse welding

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**Abstract**

The uniform pressure electromagnetic actuator (UPEA) is an innovative tool design for electromagnetic forming applications. In this article its suitability for magnetic pulse welding is demonstrated. To facilitate the process design, a simple mathematical model based on analytical equations describing the electromagnetic behavior of the system and the mechanical behavior of the workpieces under impulse loads is presented in this manuscript. The goal of the model is to predict the workpiece velocity considering the input energy, equipment and setup characteristics as well as mechanical properties of the workpiece. To validate the model, experimental analyses with aluminum-to-aluminum joints were conducted.


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## 1. Introduction

For the purpose of weight reduction and increased functionality, parts and structures in modern lightweight designs are composed of different materials. The diversity in the properties of the combined materials is particularly challenging for the joining technology [1]. In the manufacturing of such multi-material structures, conventional and widely used joining techniques often reach their technological limits. For example, due to differences in melting temperatures as well as thermal conductivity and expansion of the joining partners, thermal welding is only partly suitable for joining dissimilar materials. Furthermore, many conventional processes for joining dissimilar materials have disadvantages, which exclude them for particular applications. For instance, mechanical fastening requires the penetration of the joining partners, which might result in critical notch stresses or adhesive bonding, which often demands an intensive surface preparation.

### *1.1. Magnetic pulse welding*

A variety of disadvantages of conventional joining techniques can be avoided by the application of magnetic pulse welding (MPW). In **Fig. 1 (a)** the process principle of this joining technique is displayed.

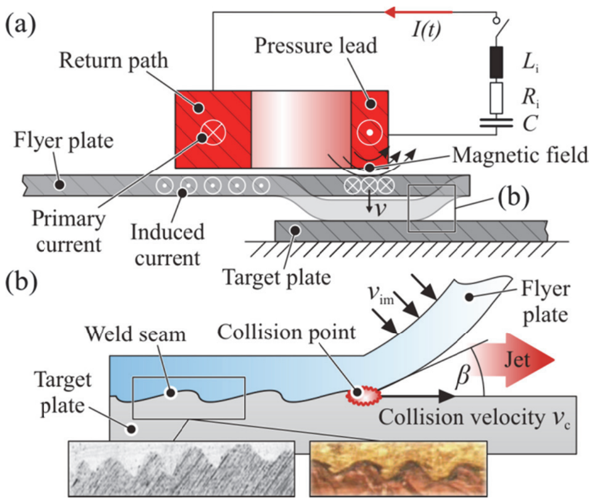


Fig. 1 (a) Process principle of magnetic pulse welding; (b) bond formation in magnetic pulse welding [1].


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This solid state welding process uses intensive magnetic pressure to drive one of the joining partners against the other one [2]. Due to a sudden discharge of a capacitor, a damped sinusoidal current *I(t)* in the magnitude of $10^4$ - $10^6$ A runs through a tool coil (see **Fig. 1 (a))**. The resulting magnetic field around the coil induces a secondary current in the conductive flyer plate, which opposes the primary one. By these opposing currents, a repulsive Lorentz force between the workpiece and tool coil is caused and the flyer plate is accelerated up to speeds of several hundred m/s [1]. Due to these high velocities, the workpieces collide under very high impact pressures. As a result, a jet is formed, sweeping away surface contaminates and forming an intimate metal-to-metal contact resulting in a metallic bond. The impact velocity $v_{im}$ and the collision angle $\beta$ are the critical process parameters which determine whether a joint is formed or not [2]. Typically, the values of $v_{im}$ are higher than 200 m/s [1] and the collision angle is between 5 and 20°, depending on the workpiece material [3]. The MPW process allows the generation of multi-material joints with very homogenous bond characteristics and almost no surface preparation [1]. Due to the absence of a heat affected zone, there is no weakening of the weld seam, which leads to a very high joint strength.

One of the major problems of MPW is the process design. Due to the very complex interactions between electromagnetic and mechanical mechanisms during the forming process, in many cases only sophisticated numerical models lead to sufficient results [2]. The computation time of such models is typically quite long and they require a comprehensive knowledge in the field of Finite Element (FE) simulation.

### 1.2. Uniform pressure electromagnetic actuator

The Uniform Pressure Electromagnetic Actuator (UPEA) was developed by Kamal et al. [4]. The tool consists of an expansion coil, which is placed in a massive copper channel (see **Fig. 2**). The channel has an opening on one side. In this area the secondary electrical circuit is closed by the workpiece, which shall be deformed. To provide a sufficient contact between channel and sheet, the copper part is pressed against the workpiece by the locking force $F_L$. The main advantages of an UPEA coil are that it generates a very uniform pressure over the forming area and it is mechanically robust [4].

In contrast to typical single turn coils for pulse welding of flat workpieces (see **Fig. 1 (a)**), the UPEA concept has multiple turns of the conductor concentrated over a relatively narrow forming zone. Since the generated magnetic field is proportional to the number of turns of the tool coil [2], with an UPEA coil, higher magnetic pressures and part velocities can be reached with lower discharge currents. These lower currents lead to a reduced wear of the EMF equipment and generally require lower charging energies to be generated.

Due to its theoretical advantages over conventional single turn coils, one objective of this work is to show the suitability of the UPEA tool concept for pulse welding applications. Another objective of this paper is the introduction of an analytical model, which describes the forming process with an UPEA coil. Hereby, the process design shall be eased. Additionally, it shall provide a fundamental process understanding.

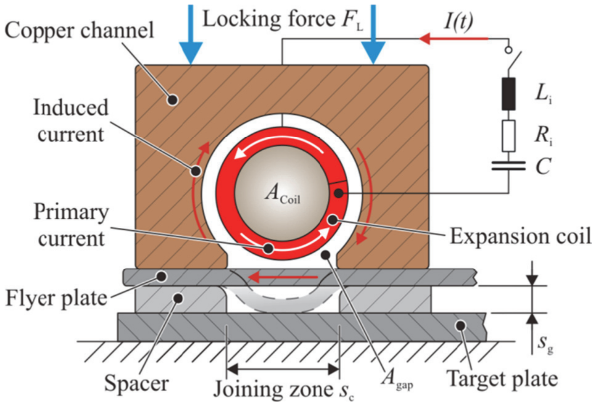


Fig. 2 UPEA actuator setup for pulse welding of flat connections.

## 2. Analytical model

The analytical model introduced here shall allow the prediction of the maximum workpiece velocity $v_{max}$ and the displacement $s_{vmax}$ at this velocity based on workpiece, tool and machine parameters. These values, combined with the knowledge of the required impact velocity to pulse weld a specific material combination, allow the estimation whether a metallic bond is formed or not. The model consists of two parts. First, discharge current *I(t)* and magnetic pressure $p_m$ are calculated. In the following section the mechanical values $v_{max}$ and $s_{vmax}$ describing the deformation are computed.

### 2.1. Prediction of the acting magnetic pressure

For the prediction of *I(t)* and $p_m$, the UPEA coil is treated as an expansion coil. To simplify the analytical model, the deformation of the workpiece was neglected for the determination of *I(t)* and $p_m$.

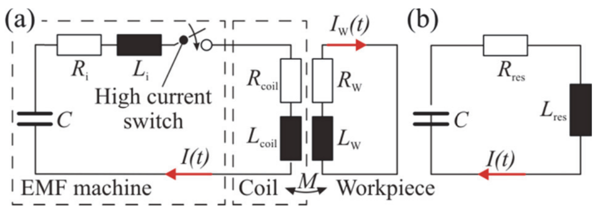


Fig. 3 (a) Equivalent circuit diagram of EMF; (b) reduced version [2].