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Vaporizing foil actuator welding as a competing technology to magnetic pulse welding

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ABSTRACT

Photonic Doppler velocimetry was applied to compare magnetic pulse welding and vaporizing foil actuator welding against each other in the form of lap joints made of 5000 series aluminum alloy sheets under identical experimental conditions which are: charging energies of the pulse generator, specimen geometry, initial distances between flyer and target plate. Impact velocities resulting from rapidly vaporizing aluminum foils were up to three times higher than those of purely electromagnetically accelerated flyer plates. No magnetic pulse welds were achieved, while every vaporizing foil experiment yielded a strong weld in that failure always occurred in the joining partners instead of in the weld seam during tensile tests. An analytical model to calculate the transient flyer velocity is presented and compared to the measurements. The average deviation between model and experiment is about 11% with regard to the impact velocity. Hence, the model may be used for the process design of collision welds generated by vaporizing foil actuators.

1. Introduction

Multi-material designs for complex lightweight applications become more and more important in the context of reducing fossil fuel consumption and subsequent exhaust emissions. Within the scope of such designs various materials are deployed with respect to the mechanical loads they are subjected to. Conventional joining techniques are not always capable of meeting the challenging requirements of those multi-material designs because of different thermal properties (e.g. melting point) of the joining partners, for example. Screw and rivet connections are usually relatively heavy and expensive, while adhesive bonding implies prolonged production times due to the curing process. As a consequence, a rising demand for alternative joining methods can be noticed. In the case of firmly bonded metals, solid-state joining of similar as well as conventionally almost unweldable dissimilar metals (e.g. steel and aluminum alloys) through high velocity forming, also referred to as collision welding, is believed to have great potential. As emphasized by Zhang (2010), another advantage of collision welding is the elimination or at least minimization of problems associated with a heat-affected zone (HAZ), such as the formation of brittle intermetallic phases or cracking in fusion welding. Consequently, the strength of collision welds can reach or even exceed the one of the weakest parent material.

2. Collision welding methods

Known collision welding methods are (Zhang, 2010): explosive welding (EXW; possible workpiece dimensions are in the order of meters), laser impact welding (LIW; dimensions of the order of millimeters), and magnetic pulse welding (MPW; dimensions of the order of centimeters). A more recent method introduced by Vivek et al. (2013) is called vaporizing foil actuator welding (VFAW; same dimensions as in MPW). The two latter methods constitute the core of the present work and are treated in more detail in the ensuing paragraphs. All mentioned joining technologies basically underlie the same physical mechanisms, which are depicted in Fig. 1.

At least one of the joining partners—the flyer—is accelerated rapidly to an appropriate velocity v_{im} at which it collides with the target plate under a certain impact angle, β, resulting in impact pressures of the order of several gigapascals (Mori et al., 2013). As summarized by Shribman (2008), this comes along with the formation of a jet that removes all oxides and surface contaminants in the weld area so that an atomic bonding can be achieved

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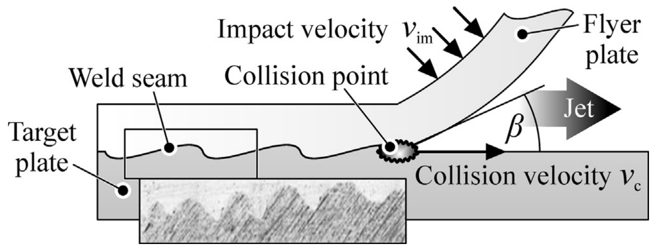

Fig. 1. Principle of collision welding (Mori et al., 2013).

between the two mating metal surfaces. The weld seam then propagates with collision velocity v_c, which is geometrically related to v_{im} through β (Mousavi et al., 2009 Mousavi and Sartangi, 2009). In the course of this, a wavy interface morphology as depicted in Fig. 1 may evolve. Regarding the actual mechanism causing such a wavy pattern, a few theories exist being still under discussion in the literature. A common explanation has been given by Ben-Artzy et al. (2010). After reviewing earlier theories, the authors experimentally established that interface waves were formed in a Kelvin–Helmholtz instability in the case of tubular MPW joints. Reflected shock waves were found to be the reason for the liquid-like behavior of the metals across their interface. Vivek et al. (2013) mention that successful welds generally occur at angles between 5° and 20° as well as at impact velocities ranging from 150 m/s to 1500 m/s. A weldability domain of the crucial parameters v_c and β required for a specific combination of materials may be represented by a so-called welding window. It also reveals whether or not waves and interlayers are observable in the weld seam. Kore et al. (2009) concluded from scanning electron microscopy (SEM) and X-ray diffraction (XRD) analysis of Mg AZ31 to Al AA3003 magnetic pulse welds with wavy interface morphology that the base materials do not undergo a melting and solidification stage. In contrast, Göbel et al. (2010) used similar techniques to prove that both intermetallic phases in “melt pockets” and virtually waveless intermetallic transition layers emerge during magnetic pulse welding of Al tubes and Cu cylinders. Welding windows originate from EXW and are derived in detail in Mousavi and Sartangi (2009) for the explosive welding of cp Ti and AISI 304 stainless steel. Verstraete et al. (2011) yet point out that impact angle and velocity are not constant during MPW, which makes the generation of such welding windows rather difficult compared to EXW. The same applies to VFAW. Vivek et al. (2014c), however, lately applied the concept of welding windows successfully to cp Ti–Cu 110 VFAW joints. Their work combined grooved target plates with predetermined angles, photonic Doppler velocimetry to record the transient flyer velocities, and SEM analyses.

2.1. Fundamentals of electromagnetic forming (EMF)

Since MPW makes use of the electromagnetic forming technology in order to join the flyer and target plate, the functional principle of EMF is briefly presented in the following. The forming tool consists of an electrically insulated coil, more generally referred to as actuator, which is connected to a capacitor bank pulse power supply (EMF machine) and at the same time placed close to the workpiece or flyer (compare Fig. 2). This entire system may be approximated by a simple series RLC (resistance-inductance-capacitance) circuit with constant elements (Winkler, 1973). The capacitor is then discharged usually within a few tens of microseconds to accelerate the flyer electromagnetically.

Beerwald (2005) enumerates that typical charging energies differ from 1 to 100 kJ, charging voltages are in the range of 3–25 kV. This results in peak currents of up to a few 100 kA. When the driving current pulse passes through the pressure lead of the coil, opposing eddy currents are induced in the workpiece under the terms of the electromagnetic laws of Lenz and Faraday. Two nearby currents flowing in the opposite direction (primary current in the coil and secondary current in the workpiece) repel each other due to the Lorentz force which acts as the forming force. High conductivity flyers may be accelerated directly in EMF, otherwise, thin high-conductivity materials can be used as a driver plate, as for example investigated by Li et al. (2013) for the electromagnetic launch of 1 mm thick Ti-6Al-4 V plates. Since the Lorentz forces take effect on both the workpiece and the coil, one of the biggest problems in EMF with regard to mass production still is the relatively short lifetime of a coil (Psyk et al., 2011). EMF coil designs can generally be classified into three categories introduced by Harvey and Brower (1958): compression coils (usually solenoids), expansion coils (also usually solenoids) as well as coils for sheet metal forming. For the latter coil type, several conductor geometries have been developed. A recent one established by Kamal (2005) is named uniform pressure electromagnetic actuator (UPEA) and was modified for magnetic pulse welding by Weddeling et al. (2014). As studied in Zhang et al. (2010), MPW coils for direct lap joints can be designed as a simple one-turn coil consisting of a pressure lead and a wider return path outside the forming area (see Fig. 2). Aizawa (2003) showed that the return path can also act as a second pressure lead if it is small enough and positioned below the target plate so that both joining partners are accelerated against each other. The coil geometry greatly influences the circuit parameters, especially the coil inductance. As explained in Daehn (2010), low capacitances and low inductances favor high frequencies which are essential for inducing intense eddy current densities and thus sufficiently high Lorentz forces in the workpiece. An upper bound for the maximum possible frequency is given by the short circuit frequency of the EMF machine. Typical values range from 20 to 100 kHz (Henselek et al., 2004).

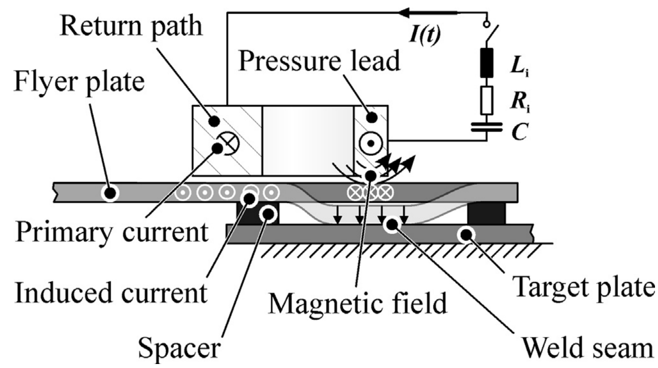

Fig. 2. Schematic of MPW for lap joints as pictured in Weddeling et al. (2014).

2.2. Fundamentals of vaporizing foil actuators (VFA)

The effects of electrically driven rapidly vaporizing foils (or wires), also referred to as electrical explosion of conductors, have been the subject of several studies over the past decades (Chace and Levin, 1960). Exemplary works include the production of nano-sized powders (Zou et al., 2012a) or the shaping of high current pulses (Bealing and Carpenter, 1972). Other common applications deal with shock wave studies (Weingart et al., 1976). However, vaporizing foil actuators have not been used for welding until the recent work of Vivek et al. (2013). In the following, the basic physical mechanisms of vaporizing conductors are outlined. VFAW basically utilizes the same machinery as EMF, but in this case the discharge current of the capacitor rapidly vaporizes a thin foil in order to launch the metal flyer plate, as indicated in Fig. 3.