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Analytical approach for magnetic pulse welding of sheet connections

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ABSTRACT

An analytical model to calculate the acting forming pressure in magnetic pulse welding by determining the magnetic field strength between the flyer sheet and a one-turn coil was presented. By neglecting plastic deformation of the flyer, the model allows to calculate the transient velocity and displacement behavior, too. The electromagnetic acceleration of 5000-series aluminum alloy sheets was investigated under various experimental parameters. Utilizing Photon Doppler Velocimetry revealed that the analytical model appropriately describes the influence of current amplitude, coil geometry, and, especially, discharge frequency on the velocity-displacement curve of the flyer and hence on the impact velocity. The model introduced was applied to compute the impact velocity for the welding of long lap joints of 5000-series aluminum alloy sheets and 6000-series aluminum alloy hollow profiles. Through peel tests it was shown that the weld strength at least complied with the strength of the weaker base material as failure always happened in the flyer sheet. The wavy interface pattern typical for impact welding was identified with the help of metallography.

1. Introduction

There is a rising demand for lightweight structures in transport-related applications with the aim of reducing energy consumption to minimize costs as well as environmental pollution so that more and more light metals are applied in the automotive industry. As a consequence thereof, manufacturers face the challenge of joining different grades of aluminum alloys. If welding is the joining process of choice, conventional fusion-based techniques often reach their limits due to the occurrence of microstructural and mechanical changes in the weld bead and heat affected zone (HAZ) reducing the strength of the joint and frequently causing hot cracks especially in welds between 5000- and 6000-series aluminum alloys (Praveen and Yarlagadda, 2005). These problems may be avoided by utilizing high velocity impact welding processes such as magnetic pulse welding (MPW). It is a solid-state welding process, which also allows to minimize or even eliminate the formation of continuous intermetallic phases when joining dissimilar metals (Zhang et al., 2011). MPW is therefore well suited for creating strong metallurgical bonds between both similar and dissimilar metals and its alloys.

The general working principle of impact welding is illustrated in Fig. 1. Besides MPW, further impact welding processes are (Zhang et al., 2011): explosive welding (EXW), laser impact welding (LIW), and the lately by Vivek et al. (2013) introduced vaporizing foil actuator welding (VFAW).

As outlined by Mori et al. (2013), the two joining partners, commonly named flyer and target, collide under the angle β at velocities v_{im} in the range of several hundred m/s producing impact pressures of the order of GPa. This process is accompanied by the so-called jetting effect that leaves behind chemically pure surfaces allowing a metallic bond to be formed. The atoms of the involved materials are impacted to such an extent that they share and exchange valence electrons. As a result, a wavy interface morphology is often observable (see Fig. 1). A common explanation for the evolution of these waves was given by Ben-Artzy et al. (2010). The authors stated that reflected shock waves in the joining partners lead to a Kelvin–Helmholtz instability. For a given material combination, the domain of the two crucial parameters β (impact angle) and v_c (collision velocity) necessary for a successful weld may be plotted in the form of a "welding window", which originates from EXW (Mousavi and Sartangi, 2009). In contrast to EXW though, both β and v_c do not remain constant during MPW (Verstraete et al., 2011). A compilation of welding windows as well as different bonding criteria available in literature so far was presented by Kapil and Sharma (2015). By means of X-ray diffraction analysis and scanning electron microscopy, Kore et al. (2009) found that neither melted zones nor intermetallic phases may be present in magnetic pulse welds, while

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Nomenclature

Symbol/meaning/unit

a	Length of the pressure lead of the tool coil in mm
$\vec{B}$	Magnetic flux density (vector) in G
B_g	Magnetic flux density in the gap between the flyer and the tool coil in G
C	Capacitance of the pulse generator in F
c_1, c_2, c_3	Constants in the analytical model
D	Flyer displacement in mm
d_1, d_2	Distances from a two-sided tool coil in mm
D_{ch}	Critical flyer displacement in the analytical model in mm
E_0	Initial charging energy in J
E_L	Total magnetic energy in J
f	Frequency of the discharge circuit in Hz
$\vec{F}_L$	Lorentz force (vector) in N/mm^3
f_0, f_d, f_b	Initial (0), Doppler-shifted (d), and beat (b) frequency of the Photon Doppler Velocimeter in Hz
F_{Peel}	Test force during peel test (index max for the maximum) in N
F_{UTS}	Ultimate tensile strength for a specific specimen geometry in N
h	Height of the tool coil in mm
$\vec{H}$	Magnetic field strength (vector) in A/mm
h'	Effective height of the trapezoidal coil in mm
H_g	Magnetic field strength in the gap between the flyer and the tool coil in A/mm
H_h	Magnetic field strength at the sidewall of the tool coil in A/mm
H_{h0}, H_{y0}	Coefficient functions in the analytical model in A/mm
H_S	Magnetic field strength due to the skin effect in A/mm
I	Coil current (index a for amplitude or peak value) in A
I_h	Current at the sidewall of the tool coil in A
I_p	Current due to the proximity effect in A
I_S	Current due to the skin effect in A
j	Imaginary unit
$\vec{J}$	Current density (vector) in A/mm^2
k	Complex propagation constant (indices F and T for flyer and tool coil, respectively) in 1/mm
l	Length in mm
L	Total inductance of the discharge circuit in H
L_i	Inner inductance of the pulse generator in H
p	Magnetic pressure (index hf for the high-frequency limit) in MPa
p_c	Plastic collapse pressure in MPa
R	Total resistance of the discharge circuit in Ω
R_i	Inner resistance of the pulse generator in Ω
s	Sheet thickness in mm
t	Time in s
t_{rise}	Current rise time in s
v	Flyer velocity (index m for measured velocities) in mm/s
v_c	Collision velocity in mm/s
v_{im}	Impact velocity in mm/s
w	Width of the tool coil in mm
w'	Width of the bottom of the trapezoidal coil in mm
β	Impact angle in °
δ	Skin depth in mm
κ	Electrical conductivity in 1/Ω
λ_0	Operating wavelength of the Photon Doppler Velocimeter in mm
μ	Magnetic permeability (index 0 for air) in Vs/Am
ρ_b	Density of the flyer material in kg/mm^3
σ_Y	Flow stress of the flyer material in MPa

Goebel et al. (2010) similarly showed that these phenomena cannot be completely avoided for some materials. In MPW the electromagnetic forming (EMF) technology is used to plastically accelerate the flyer plate. Jablonski and Winkler (1978) stated that the forming pressure in EMF is generated by penetration of a pulsed magnetic field into a conductive workpiece to be formed. The magnetic field in turn results from a rapid discharge of a capacitor through the tool coil (see Fig. 2a). Materials of low electrical conductivity can be formed with the help of thin high-conductivity driver plates (Gies et al., 2014). Such drivers are positioned between the workpiece and the coil to provide the forming pressure.

Neglecting the nonlinearity of circuit parameters due to workpiece deformation, Jablonski and Winkler (1978) described the coil current I by a simple series RLC (equivalent resistance–inductance–capacitance) circuit yielding an exponentially damped sine wave with frequency f and initial charging energy E_0:

$$I(t) = \frac{\sqrt{E_0}}{\sqrt{2C}\pi f L} \exp\left(-\frac{R}{2L}t\right) \cdot \sin(2\pi f t) \tag{1}$$

where

$$f = \frac{1}{2\pi}\sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}\,. \tag{2}$$

In order to simplify the analysis, Buehler and Bauer (1968) approximated the frequency based on the time t_{rise} until peak current I_a as

$$f \cong \frac{1}{4t_{rise}}\,. \tag{3}$$

The transient magnetic field in the vicinity of the workpiece (flyer plate) induces eddy currents in it that oppose the coil current implying the appearance of the Lorentz volume force $\vec{F}_L$ (Lorentz, 1895):

$$\vec{F}_L = \vec{J} \times \vec{B}\,. \tag{4}$$

$\vec{J}$ and $\vec{B}$ are the vectors of current density and magnetic flux density. Following Aizawa (2003), this volume force can be mathematically transformed into a pressure p, also referred to as magnetic pressure, acting on both the workpiece and the coil. It can be calculated as

$$p = \frac{B_g^2}{2\mu} \cdot \left(1 - \exp\left(-\frac{2s}{\delta}\right)\right)\,. \tag{5}$$

Here, s is the flyer thickness and B_g is the magnetic flux density tangential to the flyer surface near the tool coil. The presence of a transient magnetic field between flyer and coil leads to the evolution of two related effects, the internally caused skin and

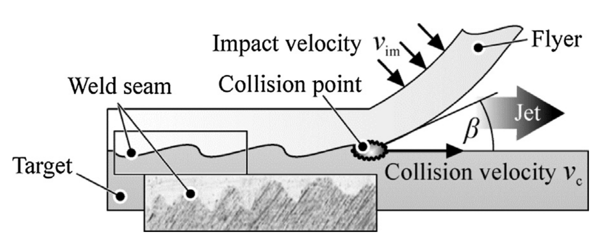

Fig. 1. Schematic of impact welding (Mori et al., 2013).