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Spatial stability analysis of emergent wavy interfacial patterns in magnetic pulsed welding

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ABSTRACT

During magnetic pulsed welding, a flier workpiece impacts a stationary workpiece to create a solid state weld. If the velocity of the flier workpiece is sufficient (e.g., >200 m/s), a wavy pattern is observed at the interface between the two workpieces. The pattern has similarities to shear instabilities observed in fluid dynamics. To investigate this behaviour and assess if a connection between the two phenomena exists, shear-flow stability analyses, informed by finite-element simulations, were performed. The results confirm that the wavy pattern can be caused by a shear instability, as hypothesized.

1. Introduction

In various industries, a desire exists to join or weld dissimilar metals. Due to the disparate melting temperatures of the materials, traditional fusion welding processes cannot be used. One means to join dissimilar metals is through magnetic pulsed welding (MPW). In this process, a capacitor bank is charged with electrical energy (on the order of tens to hundreds of kJ), which is quickly dissipated into a specially designed coil. A magnetic field is generated that induces eddy currents in nearby conductive materials. These eddy currents produce a repulsive magnetic field, and Lorentz forces cause the workpiece to deform away from the coil at a high velocity (>100 m/s). If this flier workpiece impacts a stationary workpiece, a solid state weld (or joint) can be created. MPW can be used to weld flat sheet materials as well as tubes to shafts and is closely related to electromagnetic forming; i.e., forming processes that use magnetic pressures to deform workpieces at high strain rates and in short timeframes [1].

If the relative workpiece velocity is sufficient (>200 m/s) during MPW, a distinct wavy pattern is observed at the interface between the two materials (see Fig. 1a [2]). The specific mechanism for this patterning and even the joining process, itself, is not clearly understood. Some researchers argue that localized melting and solidification at the interface occur [3], while others attribute the weld to high interfacial shear-rate deformation between the workpieces [4].

In this paper, the latter viewpoint is adopted. Moreover, the hypothesis is advanced that wavy patterns in MPW emerge as the result of a dynamic instability of a sheared visco-plastic material. Several authors, e.g., [5], have previously noted the similarity between wavy interfacial patterns in impact welding and classical

a) b)

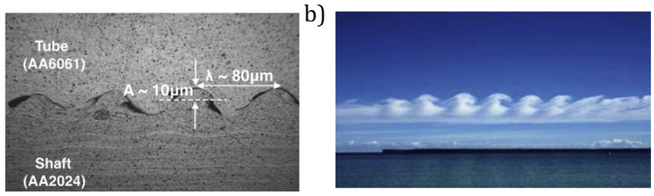

Fig. 1. Wavy patterns in (a) MPW [2] and (b) cloud formations [6].

shear (Kelvin–Helmholtz) instabilities in Newtonian fluid flows (see Fig. 1b [6]). However, none has quantitatively investigated this analogy for a plastically flowing material; rather, these prior studies implicitly assumed melting occurs in the weld zone.

Keys to this analysis are suitable (albeit abstracted) representations of the constitutive behaviour of the materials and of the profile of the "base" plastic flow at the interface. To guide the stability theory, finite-element numerical simulations are used to characterize the general shape of the shear profile, approximate the thickness of the shear zone, and estimate the material velocity close to the weld interface. With these inputs, the stability results confirm that the wavy pattern can be attributed to a shear instability between the two workpieces.

2. Mathematical model formulation

2.1. Constitutive model

When a flier workpiece collides with a stationary workpiece at high deformation rates, the stress at the impact zone increases beyond the yield point of the material and the local temperature increases at the interface. Thus, a material model that incorporates strain hardening, temperature, and strain rate effects, e.g., the Johnson–Cook constitutive model, would be the most appropriate.

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However, for stability analyses, the stress versus strain relationship must be written in tensorial form. Therefore, a simplification used here is that the material behaviour is visco-plastic, which retains strain-rate but not temperature effects.

The following additional assumptions are made: (1) the material is isotropic; (2) the flow is two dimensional and incompressible; (3) there is no strain hardening; (4) the stress and strain deviatorics are proportional; and (5) the two materials are treated as a single material with uniform material properties once joined. Note that, for the analysis, the coordinate system is defined such that the x axis is aligned with the interface, with x increasing in the direction opposite to that of weld formation, while the z axis is oriented normal to the interface. Additionally, the basic flow, $\tilde{U}_B$, is assumed to be time and x independent.

The flow is governed by the incompressibility condition and the Cauchy equation

$$\tilde{\rho}\frac{D\tilde{v}_i}{D\tilde{t}} = \frac{\partial}{\partial \tilde{x}_j}(\tilde{\sigma}_{ij}) \tag{1}$$

In Eq. (1), $\tilde{v}_i$ are the components of the velocity vector, $\tilde{\rho}$ is the material density, and $\frac{D}{D\tilde{t}}$ is the material derivative. The stress tensor, $\tilde{\sigma}_{ij}$, in Eq. (1) is defined by [7]

$$\tilde{\sigma}_{ij} = -\tilde{p}\delta_{ij} + 2\left(\frac{\tilde{\tau}_s}{\tilde{H}} + \tilde{\mu}\right)\dot{\tilde{\varepsilon}}_{ij} \tag{2}$$

where $\tilde{p}$ is the scalar pressure field, δ_{ij} is the Kronecker delta, $\tilde{\tau}_s$ is the shear yield stress of the material, and $\tilde{\mu}$ is the dynamic viscosity. $\tilde{H}$ is the intensity of shear strain rate

$$\tilde{H} = \sqrt{2\dot{\tilde{\varepsilon}}_{ij}\dot{\tilde{\varepsilon}}_{ij}} \tag{3}$$

where $\dot{\tilde{\varepsilon}}_{ij}$ is the strain rate tensor. As is clear from Eq. (2), the stress components, $\tilde{\sigma}_{ij}$, include stress terms related to plastic deformation as well as those generated by viscous resistance.

2.2. Base shear profile

For the stability analysis, the base shear profile near the interface, $\tilde{U}_B(z)$, must be specified. Commonly occurring profiles in fluid dynamics contexts include shear layers, jets and wakes; see Fig. 2. To determine which profile is most relevant for MPW, a finite-element numerical simulation was performed. As opposed to a classical Lagrangian method where the mesh is fixed to the workpiece geometry and will severely distort upon impact, an Arbitrary Lagrangian Eulerian (ALE) adaptive mesh was used in a localized region centred on the interface between the two workpieces (see Fig. 3a). Element distortion is controlled and a high quality mesh maintained throughout the simulation by enabling the mesh to adapt independently of the workpiece geometry. In this study, the ALE adaptive mesh domain was chosen to comprise the first 300 μm of the workpiece materials centred about the interface.

The numerical simulations were conducted in Abaqus using a two-dimensional plane strain model. To capture emergent wavy patterns, a very fine mesh (i.e., 5 μm) was used near the contacting edges of the workpieces. The simulations were driven by imposing a flier-plate velocity normal to the interface of 350 m/s and fixing the initial angle between the flier and stationary workpieces to be 7°. The material behaviour was modelled using a Johnson–Cook constitutive relation with the parameters for Aluminium 6061-T6 given in [8].

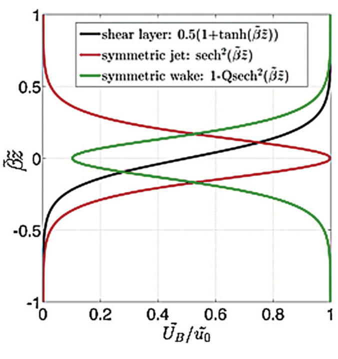

Fig. 2. Possible dimensionless base flow profiles across the interface between the two workpieces. The coordinate axes have been normalized using the velocity tangent to the interface ($\tilde{u}_0$) and the thickness of the region with significant shear ($\tilde{\beta}^{-1}$).

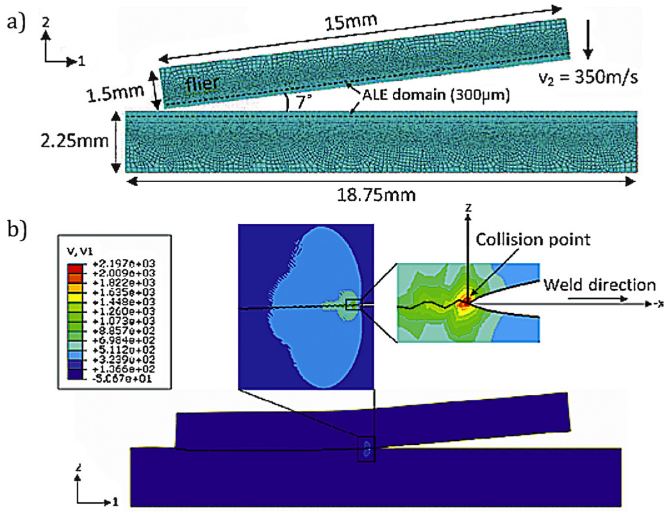

Fig. 3. Finite-element numerical simulations: (a) mesh density and (b) symmetric x-velocity profile along the interface.

The simulation results (see Fig. 3b) show the material near the collision point of both the flier and stationary workpieces moves with the same velocity (both magnitude and direction). Thus, a symmetric profile is appropriate for MPW analyses. Also, in front of the collision point, material plastically flows in the $-x$ direction, suggesting a symmetric jet-like profile would be a reasonable abstraction. However, for the stability analysis, it is convenient to adopt a reference frame moving with the collision point. In this frame, material flows in the positive x direction, and the appropriate shear profile is a symmetric wake rather than jet. (Specifically, for the results discussed in Section 4, the wake deficit parameter $Q = 0.9$ is used; see Fig. 2.)

2.3. Spatial stability analysis

There are two different types of shear flow stability analyses that can be performed, temporal and spatial. The temporal analysis assumes that the disturbance amplifies in time but not in space. In MPW, however, the instability can be introduced at a specific point, i.e., the collision point between the flier and stationary workpieces, suggesting a spatial stability analysis is more appropriate.

Fig. 4 shows a schematic of a spatially developing instability for a wake base flow. The base flow is perturbed at $x = 0$, the location of the stationary collision point, with a small-amplitude disturbance having a specified frequency ω. The analysis determines whether the perturbation exponentially decays or grows in space (with increasing x) and quantitatively predicts the associated wavelength $2\pi/k_r$ and spatial growth rate $-k_i$ (i.e., $k_i < 0$ for spatial

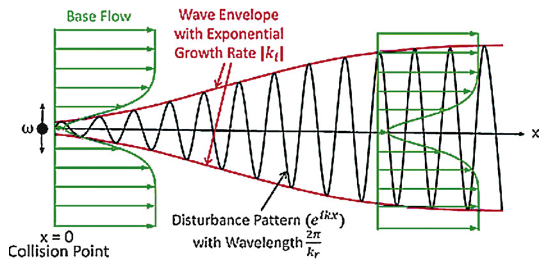

Fig. 4. Schematic of spatial shear instability. The x-dependent spatial structure of the (growing) disturbance can be represented as a complex exponential function, e^{ikx}, where $k = k_r + k_i$. Note the weld direction is to the left.