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A Complete Standard for Hypnotic Impulse Formability

Abstract

Despite its remarkable ability to join disparate materials and its environmental friendliness, magnetic pulse welding (MPW) faces a number of obstacles. Analytical calculations of the minimum impact velocity—also known as the conventional weldability criterion—as a function of material properties are used to determine the minimum impact velocity without considering the electromagnetic coil's geometry or any other electrical or physical parameters. Consequently, a sound MPW joint requires the minimum impact velocity but is not sufficient. To get around the limitations of the standard criterion, a new weldability criterion called effective impact velocity is proposed. During the process and product proving stages, the effective impact velocity eliminates the need to fabricate multiple coils and can be inversely modelled to identify shop-floor relevant process parameters. The proposed method is demonstrated through a case study of aluminum and SS304 tubular welding. The soundness of the weld that was produced using computed process parameters was confirmed by experimental observations made using lap shear tests, hardness measurements, optical and scanning electron microscopy, and surface energy dispersive spectroscopy mapping. It is anticipated that this investigation will pave the way for the creation of a process window for MPW that makes use of a variety of material combinations and will save a lot of money and time.

Keywords: Magnetic pulse welding • Weldability criterion • Bi-metallic joints • Finite element analysis • Weld interface • Metallography

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Introduction

A number of industries, including automotive, aerospace, tooling, power generation, and marine applications, have seen a significant rise in the process of combining disparate materials to create lightweight structures of the highest quality. Fusion welding joins various materials together, resulting in undesirable microstructures. Metallurgical incompatibility and the formation of brittle intermetallic compounds (IMCs) are caused by chemical interactions between materials that are not related [1]. Other issues include differences in the joint's appropriate heat treatment, galvanic corrosion, and thermal and physical properties like thermal conductivity and coefficient of thermal expansion. The design of the product and the joining process must overcome the aforementioned obstacles when joining disparate materials. Joint formation is facilitated at low temperatures and frequently very quickly, typically within microseconds, by solid-state welding methods. Cold welding, diffusion welding, vaporizing foil actuator welding, explosive welding (EXW), magnetic pulse welding (MPW), and so on are examples. By reducing the formation of harmful and brittle IMCs, these processes preserve the material's properties [2]. One of the most environmentally friendly solid-state processes for joining disparate materials is MPW, in which electromagnetic forces press one metal against another to form a solid-state cold weld. The procedure is governed by Ampere's law. The minimal impact velocity, impact angle, and interface morphology are taken into account in the investigations as indicators of the joint's success. In order to identify the parameter combinations that result in a wavy pattern, a new analytical model was recently developed [3]. The force (F) that two parallel current-carrying conductors experience in relation to their distance from one another. They provided an extensive description of the weldability limits and criterion in addition to equations for its variables and parameters in their evaluation. The one-sided minimum impact velocity criterion, also known as the threshold impact velocity criterion, can be seen as necessary but not sufficient. Material properties are used to calculate the minimum impact velocity (which will be discussed in a subsequent section). However, the actual circumstances, such as the quality of the mating surface, the geometry of the electromagnetic coil, and electrical and physical parameters like the air gap and the thickness of the tube or plate, are not taken into account by this method [4]. As a result, the calculated minimum impact velocity may not always guarantee a strong weld. There are no target velocity or process parameters specified by the minimum impact velocity criterion. After being supported by a small number of experiments, the research presented in this article suggests a computational approach for identifying target process parameters that can be used on the shop floor [5].

This study's overarching goal is to provide a numerical and experimental framework for overcoming the technical and financial barriers to the creation of MPW-based products and processes. Because the numerical algorithm used to calculate the impact velocity incorporates material properties and process parameters, the comprehensive weldability criterion in this study, effective impact velocity, is sufficient to overcome surface imperfections [6]. The investigation also demonstrates how to obtain the coil geometry and operating parameters required for shop-floor applications without having to fabricate multiple coils by inverse modeling the effective impact velocity. The following section discusses the particulars of the experimental approaches and the FEM utilized in this investigation. The methods for selecting the parameters of the process and the criteria for welding are then discussed. After the findings of this investigation have been analyzed and discussed, the effectiveness of the proposed method is then evaluated through the proximity of numerical and experimental observations on the interfacial mapping of hardness, plastic strain, and elemental distribution [7].

Metallurgical Investigation

Several phenomena occurred as a result of the flyer's material transfer to the target materials. Material transfer between the mating members caused by the high-speed impact is one reason for the increase in hardness in the interface layer or transition zone. This study looked into how process conditions affected Al/Al and Al/Cu MPW joint interface properties and weld features [8]. When joining various kinds of materials, MPW is unable to prevent the formation of an intermetallic phase at the welding interface. They discovered that Al/Al pairs produced an intermetallic phase at the bonded interface, in contrast to Al/Cu pairs. Discontinuities in flow velocity were the cause of the interface wave's effects. Waves were created across the interface by the discontinuities. Mass flow from one material to the other was caused by instabilities at the interface brought on by the disparate velocities of the two fluids [9]. The surface EDS map demonstrates that element diffusion of various materials during MPW is therefore inevitable. The formation of an intermetallic zone may be directly attributed to the atomic diffusion of one metal into the other.

The joining takes place in the middle of the mating members, with two non-welded zones on each side. The run-in and run-out zones are the non-welded zones on the left and right, respectively. At the end of the run-out zone, the flyer tube and the target tube form an angle. The run-in zone experiences a deformation that is easy to see. Deformation of the target tube decreases gradually from the run-in to the run-out zones. In the unbounded areas, the flyer tube bounces back, leaving a gap between the two plates. The numerical results demonstrate that the bonded and unbounded zones are clearly distinct. An important result of the proposed strategy is that the numerical and experimental results are comparable [10].

(b) The mechanical behavior of the joints is shown following the lap-shear test. In all specimens, fracture occurred at weaker Al and outside of the welded region, indicating that the weld was sound. This indicates that the numerically modelled process parameters passed the mechanical test, confirming the proposed method.

The proposed method was further supported by the agreement between the numerically derived plastic strain and the hardness mapping that was observed experimentally. The transition zone had the highest hardness value, 302 HV, in comparison to the typical BM hardness values of 55 HV for Al and 210 HV for SS304. The base material's hardness was lower than that of the interface layer (BM). The micro hardness immediately increased on both sides of the transition zone, and it tended to remain constant beyond these areas. The simulated strain distribution demonstrates that significant interface plastic deformation was the cause of this behavior. The unbounded run-in and run-out zones exerted less stress and strain than the bonded center zone.

A structural module for the tubes and an electromagnetic module for the coil make up a typical MPW simulation. In an electromagnetic environment, the transient magnetic forces are calculated using a nonlinear solver. The structural module is subjected to the forces in order to cause deformation. The inertial effects of time-dependent stress are taken into account by the structural module [11]. The sequentially coupled electromagnetic–structural analysis is depicted in this flowchart. The FEM model's development was guided by the assumption that cracking, friction, deformation, and joule heating all produce negligible heat. As a result, elastoplastic properties that are not affected by temperature are used. The air compression resistance between the tubes is ignored. A time-dependent multifrontal massively parallel sparse direct solver (MUMPS) and enhanced Lagrangian contact pressure were utilized [12]. This project did not make use of a field shaper. For the candidate material pair (Al–SS304), a 2D axisymmetric problem was solved using FEM in COMSOL, as will be discussed further. The flyer's geometry remained unchanged during this study's simulations. For the purposes of the simulations, the range of variation for each of the process parameters that either directly or indirectly influence the impact velocity was varied. The input voltage, coil turns, coil length, cross-sectional area, capacitance, air gap, and current frequency are among these process parameters [13].

With increasing discharge energies, the likelihood of the formation of intermetallic phases increased. When the maximum thickness of the intermetallic phase exceeds 25 meters at higher energies, the weld quality and strength suffer. The proposed method's efficacy is demonstrated by the fact that the maximum thickness that was observed using the parameters from the numerical modeling was approximately 10–12 meters. On the other hand, there were no negative effects on the interface [14]. The manner in which the two metal surfaces bind together is yet another factor that contributes to the joint's strength. Wave vortices participate in mechanical interlocking as a joining mechanism at a discontinuous interface that is mostly wavy after a high-speed collision. Al's low strength and high ductility encourage interlocking when compared to SS304. This is similar to the combing action, in which a low-strength alloy can penetrate a high-strength alloy and cause mechanical interlocking, in differentiating friction stir welding. However, depending on the characteristics of the swirl-affected zone, the concept of interlocking in MPW may also be a defect site. This is especially true in the case of MPW between different materials, where a strong swirling motion at the bi-metallic interface can lead to the formation of the intermediate phase, which has a big effect on the properties of the weld. In order to meet the weldability requirement and allow for a significant thickness reduction in the intermediate phase, it is necessary to have the appropriate input parameters [15].

Conclusions

A new weldability criterion for MPW is presented in this study, and it offers a cost-effective and timely approach to process development. The following are the main findings of this study:

Because it is calculated using material properties without taking into account the electromagnetic coil's geometry, electrical and physical parameters like air gap and plate thickness, or surface imperfections, the conventional weldability criterion (threshold impact velocity) is necessary but insufficient. It is impossible to identify process parameters suitable for use on the shop floor using this criterion.

The effective impact velocity, which is the average of the maximum possible velocity without causing damage, is the new criterion that has been proposed. The investigation provides a numerical algorithm for calculating effective impact velocity, and the maximum velocity that can be achieved without causing damage is calculated using FEM simulation.

Because it can be numerically computed and inversely modelled, the proposed weldability criterion overcomes the limitations that are currently in place and can be used to prescribe process parameters that are applicable to the shop floor.

In terms of the distribution of plastic strain, the morphology of the interface, and the width of the intermediate layer, the numerically computed parameters used to produce the weld samples were in line with the results of the experiments. Because the increased hardness in and around the interface zone corresponded to the predicted plastic strain in the FEM simulation, the joints passed lap shear tests without breaking outside the welded region. Additionally, the increased hardness was linked to element transfer at the interface during the severe plastic deformation at the time of impact, as demonstrated by surface energy dispersive spectroscopy.

Because it saves time and is supported experimentally, the proposed strategy will encourage the use of finite element modeling to obtain shop-floor-applicable process parameters. Additionally, the use of a small number of electromagnetic coils, as opposed to multiple coils in conventional methods, will result in lower FEM validation costs.

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