Journal of the Mechanics and Physics of Solids 96 (2016) 147–161

Contents lists available at ScienceDirect

Journal of the Mechanics and Physics of Solids

journal homepage: www.elsevier.com/locate/jmps

Interfacial kinematics and governing mechanisms under the influence of high strain rate impact conditions: Numerical computations of experimental observations

R.N. Raoelison [a,b,*], T. Sapanathan [b], E. Padayodi [a], N. Buiron [b], M. Rachik [b]

[a] Université de Bourgogne Franche Comté, Université de Technologie de Belfort Montbéliard, IRTES EA 7274, 90100 Belfort, France
[b] Sorbonne universités, Université de technologie de Compiègne, Laboratoire Roberval, CNRS UMR-7337, Centre de recherche de Royallieu, CS 60319, 60203 Compiègne cedex, France

A R T I C L E I N F O

Article history:
Received 28 May 2016
Received in revised form 15 July 2016
Accepted 19 July 2016
Available online 21 July 2016

Keywords:
Interfacial kinematics
Numerical simulation
Wavy interface
Jet formation
Impact mechanics

A B S T R A C T

This paper investigates the complex interfacial kinematics and governing mechanisms during high speed impact conditions. A robust numerical modelling technique using Eulerian simulations are used to explain the material response of the interface subjected to a high strain rate collision during a magnetic pulse welding. The capability of this model is demonstrated using the predictions of interfacial kinematics and revealing the governing mechanical behaviours. Numerical predictions of wave formation resulted with the upward or downward jetting and complex interfacial mixing governed by wake and vortex instabilities corroborate the experimental observations. Moreover, the prediction of the material ejection during the simulation explains the experimentally observed deposited particles outside the welded region. Formations of internal cavities along the interface is also closely resemble the resulted confined heating at the vicinity of the interface appeared from those wake and vortex instabilities. These results are key features of this simulation that also explains the potential mechanisms in the defects formation at the interface. These results indicate that the Eulerian computation not only has the advantage of predicting the governing mechanisms, but also it offers a non-destructive approach to identify the interfacial defects in an impact welded joint.

1. Introduction

Adaptation of high speed joining techniques allows various possibilities to produce successful joints for similar and dissimilar metal combinations than several years ago. In the past, fusion welding was applied to metallurgically compatible materials, whose melting temperatures are similar to obtain successful joints. However, the new developments provide wide range of options to join metals with various melting temperatures, thus such welding methods eliminate the limitation of a fusion welding. In this way, the following welding methods become examples of high strain rate joining methods, viz., explosive welding (Gülenç et al., 2016), laser spot welding (He et al., 2003), magnetic pulse welding (Shribman, 2008), vaporized foil actuator welding (Vivek et al., 2014) and various friction welding process. Particularly those belong to high

* Corresponding author at: Université de Bourgogne Franche Comté, Université de Technologie de Belfort Montbéliard, IRTES EA 7274, 90100 Belfort, France.
E-mail address: rija-nirina.raoelison@utbm.fr (R.N. Raoelison).

http://dx.doi.org/10.1016/j.jmps.2016.07.014
0022-5096/

speed impact welding (HSIW), effectively utilizes the synergic effect of very high contact pressure in the range of 1-10 GPa and very short duration of the application time (i.e. a few hundred microseconds), thus these methods avoid the additional requirements of controlled heating or brazing. Using HSIW methods one could fabricate similar and dissimilar metal joints such as Cu/Brass, Cu/steel, Cu/Al, Al/steel, Ti/steel, Cu/Ti, Al/Mg, Al/Ni, Al/Fe, Al/Ti, Ti/Ni (Shribman, 2008; Shribman et al., 2001; Jassim, 2010; Findik, 2011; Raoelison et al., 2012a, 2012b, 2014; Baaten et al., 2010; Yu et al., 2013; Mroz et al., 2015) Cu/Zr metallic glass (Hutchinson et al., 2009), Al/Zr-Cu metallic glass (Watanabe et al., 2009), Al/Fe metallic glass (Liu et al., 2009), Cu/Manganin (Kashani et al., 2009), flexible circuit boards (Aizawa et al., 2013), W/CrCuZr (Sun et al., 2014), and multilayered dissimilar component; viz., Al/Cu/Al (Sedighi and Honarpisheh, 2012),Ti/mild steel/Ti (Bae et al., 2011) and Al/steel/Al (Gülenç et al., 2016).

The magnetic pulse welding (MPW) particularly has the advantages of flexibility, applicability, less requirement of energy due to short duration of process time, reduced cost, no requirements of consumables and environmental friendliness (Kapil and Sharma, 2015). The Lorentz force generated as a result of electromagnetic impulse is effectively utilised to achieve successful collision for a MPW. It is also possible to obtain various coil designs for specific applications and which are capable of generating complex distribution of Lorentz forces (Psyk et al., 2011). According to a comprehensive review on this topic, the growing interest of this process is given by various industries, viz., automobile, aerospace, nuclear, electrical and microelectromechanical systems, ordnance and packaging while some of its applications are being industrialised (Kapil and Sharma, 2015). Moreover, this process has various practical benefits and it is mainly suitable to fabricate tubular assemblies, flat shape connections and regular or irregular components. Although MPW has its unique characteristics, the interfacial behaviours and its interfacial kinematics are comparable to other HSIW processes (Verstraete et al., 2011; Reid, 1974, 1978).

During a HSIW, the notion of weldability is subjected to the complex interfacial kinematics. The interface morphology is mainly investigated to determine the formation of a successful joint. Generally, it is widely accepted that the formation of an interfacial wave produces a successful bonding; thus, various research studies were carried out to determine the favourable condition for such wave formation. Available theoretical literatures on this topic present the correlations between the material properties and dynamic interfacial parameters, based on analytical descriptions of the interface behaviour under hydrodynamic considerations. Various models were suggested to identify the onset of wavy pattern (Athar and Tolaminejad, 2015). However, the existing analytical models are inadequate and reveal real difficulties of experimental conditions due to various factors. Those generic models do not include the high strain rate sensitivity of materials that governs the mechanical deformation and subsequent dynamic behaviour during the collision. Instead, those models include mechanical properties such as hardness and yield strength; and they generally rely on restrictive geometrical parameters that may lead to a poor representation of the real scenario and deviate from the real response of the interface (Lysak and Kuzmin, 2012; Walsh et al., 1953; Cowan and Holtzman, 1963; Wittman, 1973; Deribas et al., 1975; Crossland, 1982; Belayev et al., 1978; Shmorgun, 1988). Moreover, some other models are described by a set of dynamic parameters including collision velocity (collision propagation velocity) and dynamic collision angle (impact angle) whose real experimental values are very difficult to obtain at present (Deribas et al., 1975; Crossland, 1982; Belayev et al., 1978; Shmorgun, 1988). Random evolutions of those parameters can also occur along the interface as the heterogeneous progression of the collision depending on the mechanical deformation of the interface. Furthermore, semi-empirical depictions of the weldability do not concur those analytical models. In a collision angle vs. collision velocity coordinate, the experimental lower limit can have an increasing downward curve (Zhang et al., 2010; Grignon et al., 2004; Uhlmann and Ziefle, 2010) in contrast with the generic theoretical models. Danesh et al. have also considered a range of welding natures using several interfacial parameter sets (impact velocity, impact angle, normalized normal stress, specific pressure, deformation ration) and identify the important deviations with respect to experimental observations (Dhanesh et al., 2011).

A recent theoretical investigation suggests more complex weldability ranges including specific influence on a coordinate system of inertia, time and pressure (Lysak and Kuzmin, 2012). Many interface variances were also depicted to represent a 3D weldability range that consists of pre-critical zone (no welding), wavy zone (welding zone), waveless zone, anomalous wave zone, melt solidification zone, and supersonic zone (Lysak and Kuzmin, 2012). Although, the pragmatic assessment of those analytical zone limits is defined by the collision angle and collision velocity, it again remains difficult as for the same reasons mentioned above. A reliable weldability depiction should include the multi-physics, kinematics and transient response of the interface during the collision. Under such conditions, the numerical simulation is a crucial and powerful tool that can assist to perform realistic virtual tests and predict the weld variance originated from the complex interface behaviour during the welding processes. In order to accomplish this purpose, this study proposes a computational method that enables to reproduce the interfacial characteristic changes. Prior to proceeding to the details of this method, this study also includes an assessment of the existing literatures on numerical simulations of high speed impact welding methods and summarizes them. These interfacial characteristics are identified as the main mechanisms those govern the experimentally revealed interfacial features. A discussion on the adequacy of the computational method is provided; then it highlights such interfacial characteristics and compares them in terms of complex interfacial kinematics and defects' morphology of welded interfaces.

2. Merits and limitations of existing impact welding simulations

Regarding the computation of weld formation during high speed impact welding processes, a limited literature is