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Benjamin Zielinski, Tarik Sadat, Bratislav Lukić, Grégory Haugou, Hervé Morvan, et al.. Characterization of local mechanical properties of Al/Cu Magnetic Pulse Welded joints under high strain rates using synchrotron X-ray imaging. *Materials Letters*, 2023, 337, pp.133943. 10.1016/j.matlet.2023.133943 . hal-04085480

HAL Id: hal-04085480

<https://uphf.hal.science/hal-04085480>

Submitted on 29 Apr 2023

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Title: Characterization of Local Mechanical Properties of Al/Cu Magnetic Pulse Welded Joints under High Strain Rates using Synchrotron X-ray Imaging

Authors: Benjamin ZIELINSKI ^{1*}, Tarik SADAT ¹, Bratislav LUKIĆ ², Grégory HAUGOU ¹, Hervé MORVAN ¹, Alexander RACK ², Eric MARKIEWICZ ¹, Laurent DUBAR ¹

Affiliations :

¹ Univ. Polytechnique Hauts-de-France, CNRS, UMR 8201 – LAMIH – Laboratoire d’Automatique de Mécanique et d’Informatique Industrielles et Humaines, F-59313 Valenciennes, France

² ESRF – The European Synchrotron, CS40220, CEDEX 09, 38043 Grenoble, France

Corresponding author: benjamin.zielinski@outlook.com

Abstract:

Magnetic Pulse Welding (MPW) is a method of growing interest allowing the joining of dissimilar materials such as aluminum and copper. The global mechanical properties of the joint are often evaluated with conventional tests, using the fully welded joint. However, these cannot elucidate the local mechanical properties of the joint or its interface when subjected to high strain rates loads. Cubic samples of Al/Cu have been designed and extracted from MPW joints, in order to locally characterize the mechanical properties. Samples were exposed to high strain-rate loading using the Split-Hopkinson Pressure Bar (SHPB) coupled to ultra-fast synchrotron X-ray radiography in order to investigate related failure processes *in-situ*. The measurements of the interface evolution were related to the macroscopic applied load. In addition, synchrotron microtomography was performed on the samples before mechanical deformation. Aside from the feasibility proof, this work provides, for the first time, the correlation of the interfacial opening evolution and the influence of pre-existing cracks of the weld. It is observed that, the pre-existing cracks at the interface correspond to the initiation sites of interfacial separation between the two dissimilar metals.

Keywords: Deformation and fracture, Interfaces, Metals and alloys, X-ray techniques, Welding

1. Introduction

Over the last decade, industrial effort has been put into the reduction of the carbon footprint in order to reach the normative targets for the ecological transition [1]. For instance, automotive industry has been

concentrated on reducing its environmental impact by decreasing the vehicles fuel consumption or electrifying the vehicles, hence decreasing CO₂ emission. This strategy results in a continuously increasing use of aluminum and copper, especially from the aspect of the electrical connections within battery packs [2]. The assembly of these two dissimilar materials demands the use of new process techniques which will insure reliable assembly with high-quality mechanical properties. Magnetic Pulse Welding (MPW) is a recently introduced process which allows the welding of plates made of different metals [3]. Several examples of successful assemblies of dissimilar materials have been demonstrated, such as Al/Fe [4], Al/Cu [5]. Typically, the mechanical properties of the resulting joints are tested with a standard mechanical test (*i.e.*, tensile or lap shear test [6]). This work aims to locally investigate compressive behavior of these joints under high strain rates by the mean of a Split-Hopkinson Pressure Bar (SHPB). Ultra-fast X-ray radiography is used to probe the *in-situ* deformation simultaneously to the mechanical load measurements, allowing to evaluate the evolution of the welding at the interface. The combination of these data allows to determine the damage experienced by the joint by analyzing its spatio-temporal evolution.

2. Materials and Methods

MPW joints have been fabricated by assembling commercially available components, a 1050 aluminum (Al) of 98x30x1 mm³ and copper (Cu) of 98x30x2 mm³ plates. Aluminum was used as the flyer, while the copper was the base part. The assembly was performed with a PULSAR 25 kJ-9 kV device with a 690 μF condenser at a frequency of 25 kHz. The parameters have been set to: an energy of 19.4 kJ, an initial gap of 2 mm and an overlapping between the sheets of 7 mm, based on previous studies [7]. Cubic samples of 3 mm³ have been extracted from various locations on the central joint area by Wire-Cut Electrical Discharge Machining (WEDM) as presented in Fig. 1-(a) and 1-(b).

The SHPB device located at the ID-19 beamline of the European Synchrotron Radiation Facility (ESRF, France) [8], has been designed to exploit the large hutch space and hence accommodates both the input and output bars which are 1300 mm and 1100 mm long respectively, having a diameter of 12.7 mm. Bars and projectile are made of PH 17-4 steel with a H900 thermal treatment giving a yield strength of 1.2 GPa and a wave speed of 5020 m/s. A 150 mm long projectile moving at 12 ± 1 m/s was used to create an incident compressive pulse transmitted to the sample.

Ultra-fast *in-situ* X-ray radiography [9], was used by exploiting the 16 bunch-filling mode. X-ray signal was converted with a fast scintillator to a visible spectrum and optically relayed to an ultra-high-speed Shimadzu HPV-X2 camera [10]. A magnification of X4 was used with a resulting 8 μm pixel size. The acquisition was set to record 128 images during the test, with an inter-frame time of 1930 ns.

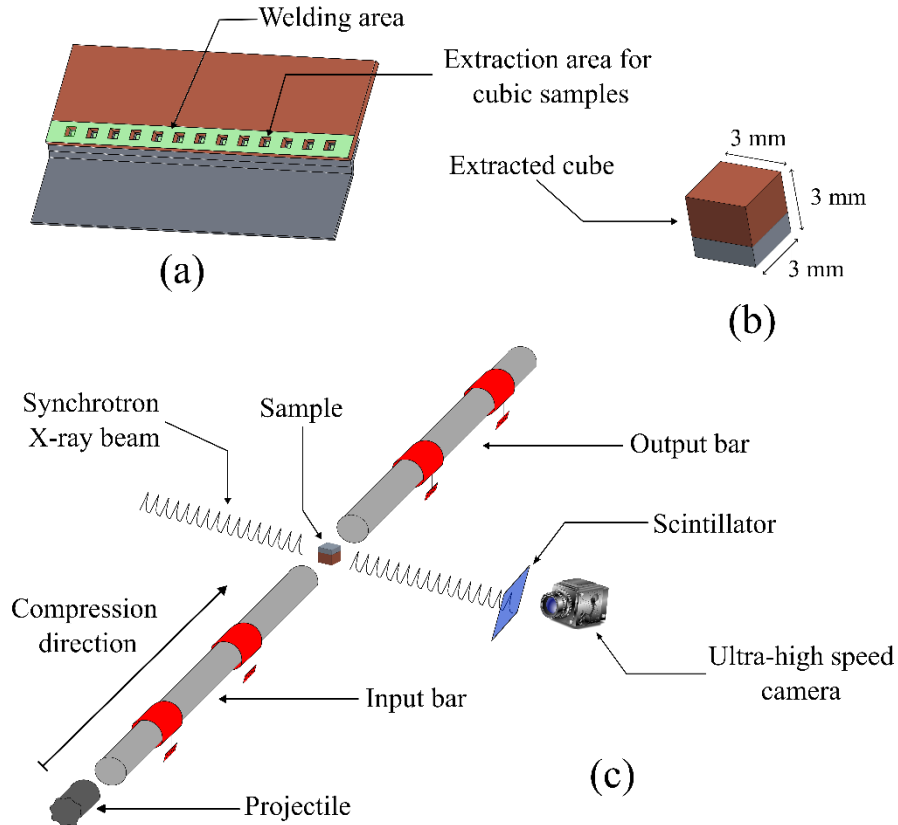


Fig. 1. (a) Scheme of the MPW joint and the cubic samples extraction area, (b) Geometric scheme of the extracted cube, (c) Scheme of the experimental set-up of the samples with the SHPB, X-ray beam, and location of the ultra-high speed camera. [Color/2columns]

Samples were positioned such as to have the bi-material interface parallel to beam axis. The entire experimental set-up is depicted in Fig. 1-(c).

3. Results and Discussion

Four samples were tested with an average strain rate being $3250 \pm 250 \text{ s}^{-1}$ for a total deformation of 40%. Two distinctly different types of behaviors were observed from the radiographs data, with test cases presented in Figure 2 (available in the Supplementary Material).

Three geometric metrics have been extracted to describe the interfacial opening, corresponding to height, width, and the surface of the opening, schematized in Fig.2-(i). These metrics have been analyzed in the time and correlated to the applied force as measured from the deformation waves recorded on the SHPB as shown in Fig. 3.

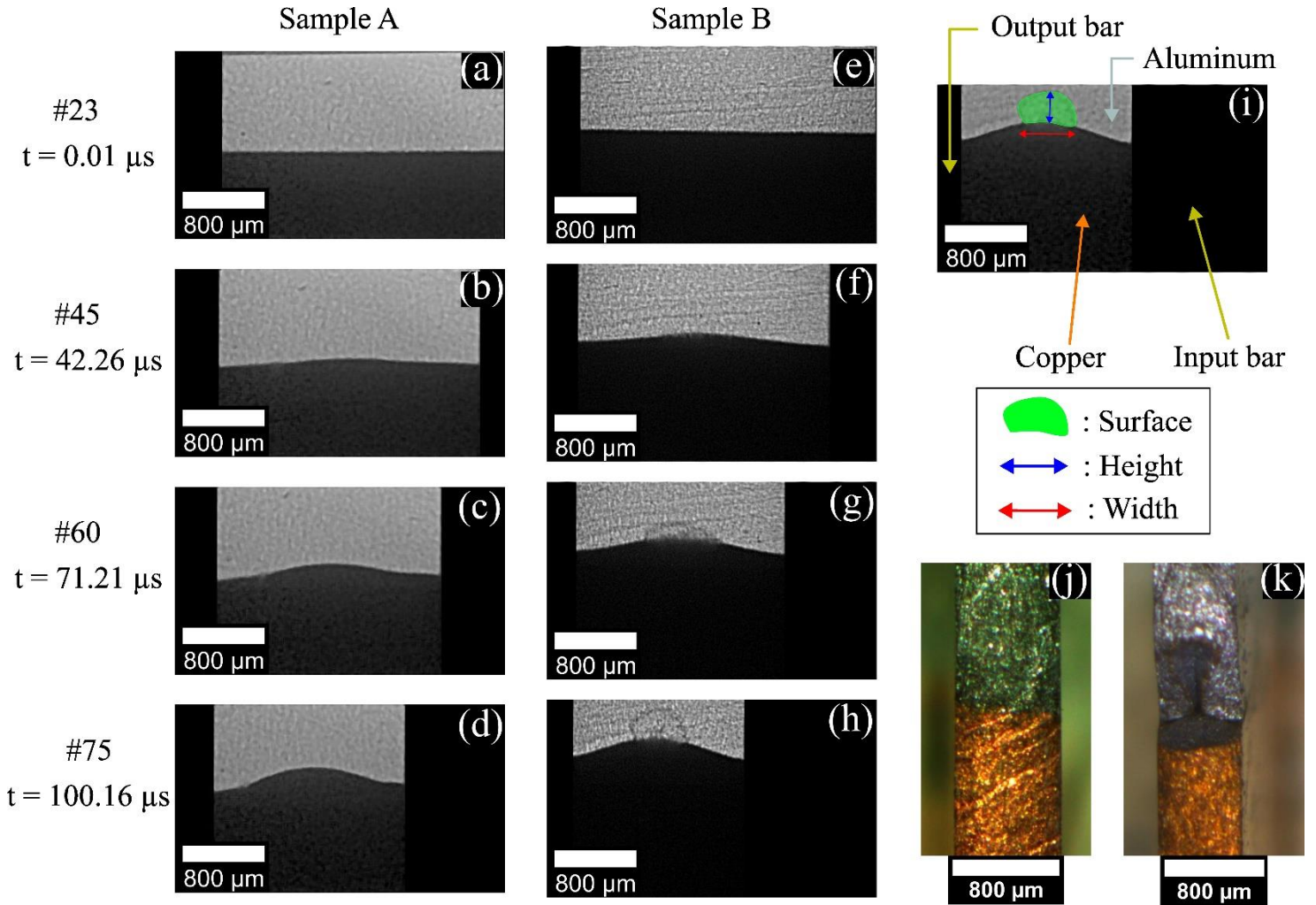


Fig.2 (a-d) Interface radiographs evolution for sample A, (e-h) Interface radiographs evolution for sample B, (i) Description of the computed metrics at the interface, (j) Sample A *post-mortem* interface without opening, (k) Sample B *post-mortem* interface with opening [Color/two columns]

Fig. 2-(a-h) illustrates four radiographs of Al/Cu welded samples interface during the SHPB impact test. Samples exhibit a curvature at the Al/Cu interface due to barreling during compression. Regarding Sample A, Fig. 2-(a-d), the interface remains continuous throughout the test. There is no clear separation between the aluminum and the copper at the interface. The welded interface is visible in Fig. 2-(j) in *post-mortem* condition. On the other hand, Sample B, Fig. 2-(e-h), reveals a pronounced opening at the center of the cube between the two interfaces as the loading increases. Fig.2-(k) displays the opening in *post-mortem* condition.

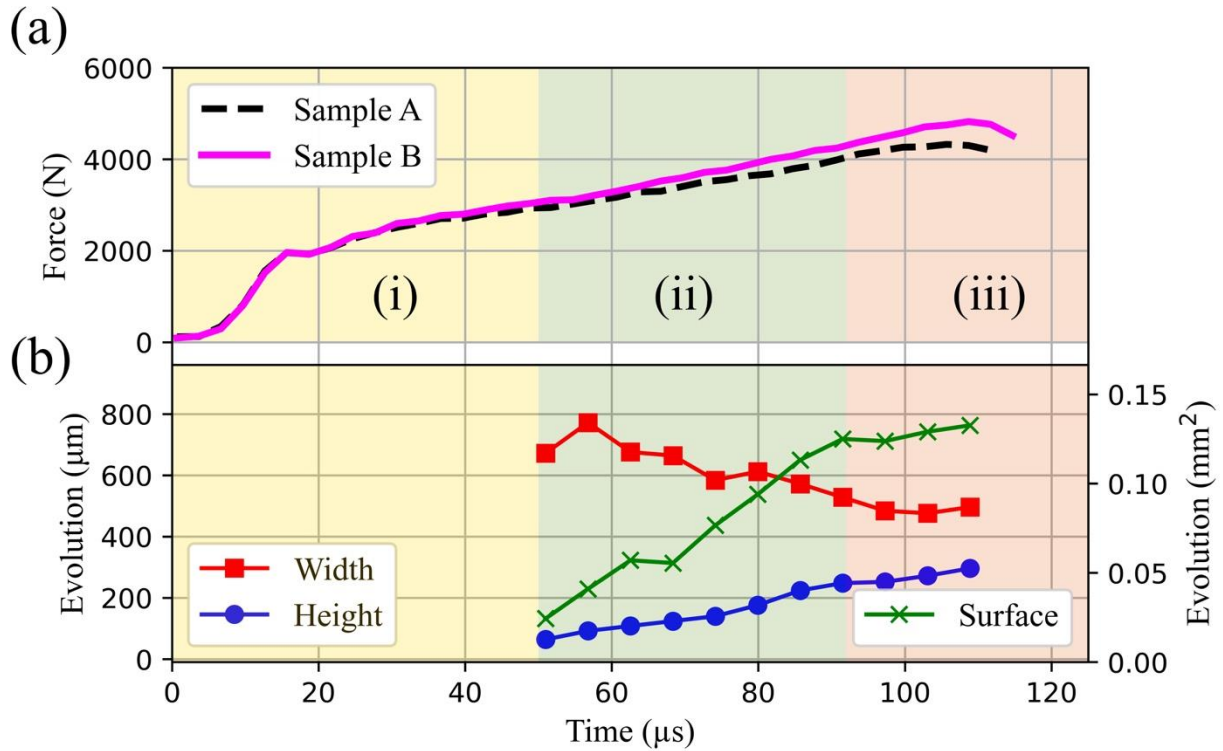


Fig. 3 (a) Applied Force on the samples as a function of the time, (b) Morphological measurements of the opening as a function of the time of Sample B [Color/two columns]

Both samples A and B exhibit the same trend of macroscopic mechanical response (Fig.3-(a)), whereas, there is a clear difference at the interface in terms of mechanical behavior between the two samples as illustrated by the opening in sample B (Fig. 2). Three deformation domains have been identified and presented in Fig. 3: (i) Macroscopic deformation without visible opening at the interface, (ii) Increasing of the opening, (iii) Stabilization of the surface opening. The opening grows continuously in height, whereas for the width, it reaches a maximum and then starts to decrease. This indicates that the opening at the width cannot propagate along the interface.

Samples A and B were scanned prior to mechanical tests using microtomography capabilities of ID19 with synchrotron pink beam and propagation-based phase contrast mode resulting a 1.43 μm voxel size. Fig. 4 displays two tomographic slices of the samples before impact. Clear micro-structural differences are observed at the interface between samples A and B. This demonstrates the non-homogeneity of the weld according to the sample's location. At the welded interface of Sample A, in Fig. 4-(a), there is no crack between the two compounds. On the other hand, in Fig. 4-(b), a continuous crack is present on the left side of the assembly interface of Sample B. The crack has an average length of about 1450 μm and a maximum opening of 21.5 μm . This zone corresponds to pre-induced damage that have been initiated during the fabrication of the assembly. This cracked interface cannot carry the applied load on the sample but will rather re-open, which can explain the difference in behaviors between the two samples as observed from the data presented here-in.

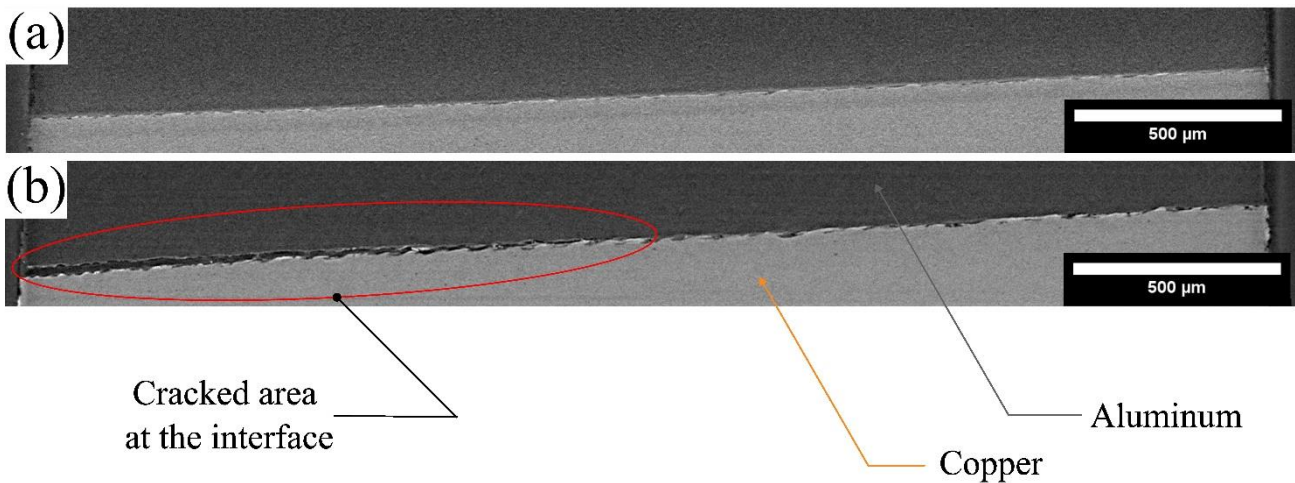


Fig.4 (a) Tomographic slice from Sample A without any continuous cracks at the interface, (b) Tomographic slice from Sample B with a continuous crack at the left side of the interface [Color/two column]

4. Conclusions

Mechanical properties of MPW joints have been investigated to locally deform the joint under high-strain rates compression. *In-situ* X-ray radiographs have been used to determine the damage evolution during the tests. The method has been successfully applied exploiting the full imaging capabilities of the ID-19 beamline (ESRF).

The results demonstrate that pre-existing cracks within the welded samples can initiate an opening between the two interfaces of the MPW joint when mechanically loaded. However, the opening does not appear to propagate along the entire length of the interface. It is also important to note that samples with a joint locally in good condition (*i.e.* without visible damage) did not present any opening between the two interfaces.

Credit authorship contribution statement:

Benjamin Zielinski: Writing – Original draft preparation, Software, Methodology, Investigation. **Tarik Sadat:** Writing- Reviewing and Editing, Software, Methodology, Investigation, Validation. **Bratislav Lukić:** Reviewing, Investigation, Resources. **Grégory Haugou:** Software, Formal analysis. **Hervé Morvan:** Software, Data curation. **Alexander Rack:** Supervision. **Eric Markiewicz:** Supervision, Resources, Project Administration. **Laurent Dubar:** Supervision, Resources, Project Administration.

Funding: This research did not receive any specific grant from funding agencies in the public, commercial or nonprofit sectors.

Acknowledgements: The authors thank the platform PFT Innovaltech (France) and M. Denis JOUAFFRE for the welded samples preparation. The authors further acknowledge ESRF and ID-19 staff for the beamtime and deep involvement during and after the experiments.

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