IOP Conf. Series: Materials Science and Engineering **118** (2016) 012016 doi:10.1088/1757-899X/118/1/012016

Microstructural characterisation of interfaces in magnetic pulse welded aluminum/aluminum joints

S Sharafiev[1], C Pabst[2], M.F.-X Wagner[1] and P Groche[2]

[1] Chair of Materials Science, Institute of Materials Science and Engineering, Technische Universität Chemnitz, D-09125 Chemnitz, Germany
[2] Institute for Production Engineering and Forming, Technische Universität Darmstadt, D-64287 Dramstadt, Germany

Abstract. Electromagnetic pulse welding provides novel and useful solutions in the field of multi-material structures. The joining occurs through the high-energy mechanical impact of metal sheets, which leads to a strong, cohesive, metallic bonding between the sheets. The high-velocity collision results in changes of the microstructure in the regions adjacent to the interface. The aim of this work is the microstructural characterization of the interface and the welding zone of Al/Al joints. One typical interface is analysed by optical and electron microscopy and using the electron backscatter diffraction technique. Our results show that the interface exhibits a well-known type of wavy weld geometry. Moreover, the formation of an intermediate layer that is different from the bulk aluminium structure is observed. The microstructure of this intermediate layer consists of ultrafine grains and in some regions exhibits a columnar grain structure. It is likely that this special microstructure (which plays an important role in determining the cohesive, continuous bonding between the metal sheets) is formed through a rapid melting and crystallisation process in the interface region.

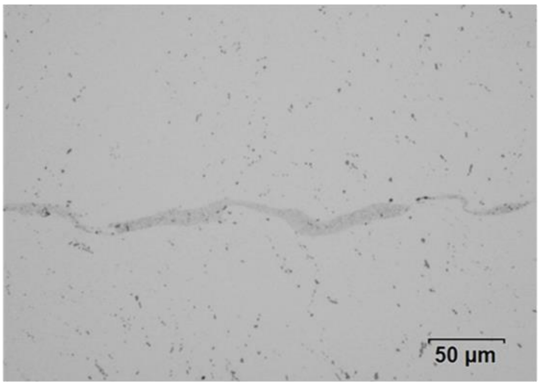
1. Introduction
Electromagnetic pulse welding (EMPW) is a widely used technique to produce joints between metal sheets by plastic deformation. The joining is achieved by the collision of two partners after acceleration of the dynamic partner (flyer) towards the other, static partner (target). The bonding processes take place at very high strain rates up to 10^6 s^{-1}. EMPW is increasingly used in industrial applications, even though there exists only limited knowledge of the bonding mechanisms. In most scientific studies, the characterisation of welding zones is limited to a macroscopic evaluation along the weld. For a more detailed understanding of EMPW it is necessary to analyze the microstructural changes in the interfacial region, where continuous metallic bonding leads to the adhesion between the metal joint partners. This may in turn allow to define useful processing regimes, such as impact velocities and angles that lead to proper joining along larger welding zones.

2. Experimental
In the present study the microstructure in an interface between two magnetic pulse welded pure aluminum sheets (EN AW-1050) was investigated. The sheet thickness was 2 mm. The EMPW process was carried out with an initial distance between plates of 2 mm. The electrical current ranged between 322 – 397 kA at 18.9 kHz. Further information on the industrial EMPW setup used for joining is presented in our previous work [1]. The structural changes in the welding zone were observed by optical (OM), scanning electron (SEM) and transmission electron microscopy (TEM)

with selected area electron diffraction (SAED). In addition, electron backscatter diffraction (EBSD) measurements on the interface were carried out in the SEM. The samples were ground and polished for OM. Ion beam thinning and polishing were applied for the observations by TEM. A vibration polishing procedure was applied for the SEM and EBSD measurements.

3. Results and discussion

Focusing on the characterisation of the interfacial changes, which lead to the cohesive bonding between two aluminium sheets, only regions within the seam with wave formation and an intermediate layer are discussed here. For microscopic observation, the joints were cut along the cross-section in the weld centre, so that the cutting plane is perpendicular to the sheet plane and parallel to the direction of weld propagation. In this cross section the interface exhibited a typical wavy morphology, as can be seen in optical overview micrograph in figure 1. It should be noted that we do not address questions related to wave formation (such as wave length as a function of different impact conditions) in this short paper. This topic of wave formation during impact welding has been extensively discussed in other studies such as, for instance, in [2]. One important and general observation when studying EMPW-produced interfaces of aluminum materials is that even between similar aluminium/aluminium joints, some special microstructure can be always found in the weld zone. This interfacial microstructure is typically referred to as "intermediate layer", see e.g. [3]. The microstructure of this layer differs from that of the initial bulk material. Its thickness is about 5 – 15 µm. We found that this intermediate layer was unstable against the etching procedure typically used for aluminum alloys. Assuming that the so-called jet clears the sheet surface during the welding process [4] it is unlikely that the intermediate layer consists of surface aluminium and/or oxide particles. Instead, we propose that the changed microstructure is formed in the near-interface region during welding process and that it is characterized by a higher defect density, which makes it prone to removal during conventional etching.

(a) 

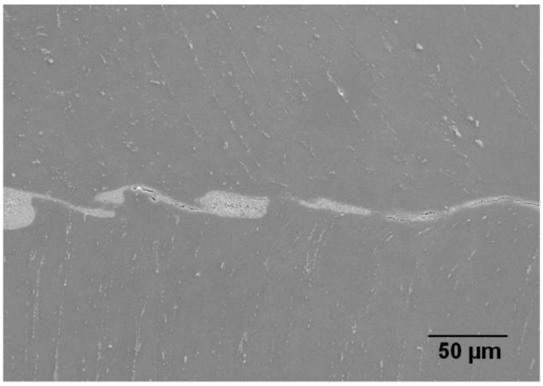
(b) 

Figure 1. Overview of the interface of an aluminum/aluminum joint produced by EMPW. The interface exhibits a characteristic wavy form and the intermediate layer differs from the initial bulk material: (a) OM image, (b) SEM micrograph.

For a detailed observation of the grain structure in the intermediate layer, the EBSD measurements were carried out. It should be noted that the preparation procedure for EBSD analysis needs to provide pristine surfaces, i.e., it requires a careful and time-consuming procedure to make sure that particularly the unstable microstructures near the weld zone are not affected. In figure 2, we present a representative SEM micrograph, and a corresponding EBSD image, of the welding zone. Compared to the initial grain structure, the much finer grain structure in the intermediate layer can be clearly seen in the EBSD image. Furthermore, mainly on the right part of the EBSD image, the grains exhibit a columnar shape. These columnar grains are elongated in the direction of the acceleration vector during EMPW. This specific feature of the weld zone region can be compared with the structures of grain growth in the presence of a strong temperature gradient. The microstructural features documented in figure 2 indicate that the material may well have been melted for a very brief period of time during impact welding: this local melting in a very thin surface region of the aluminum parts can result from the high impact energies during EMPW. This energy is expended on the deformation in the initial bulk material and (because of the very high strain rates) leads to near-adiabatic heating. Subsequent rapid crystallisation due to the high temperature gradient between the surface layer and the bulk material then leads to the elongated, columnar microstructures. We note that, considering the complex dynamics of impact welding, the tensile pulse directly after impact might also have an effect on the growth process; further work is required to analyse this effect in detail.

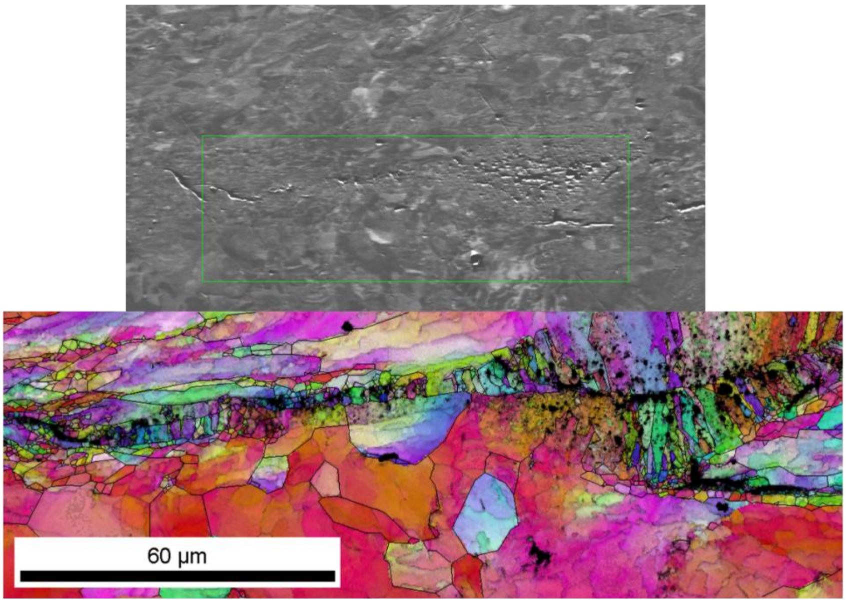


Figure 2. SEM micrograph and EBSD image of the welding zone; the green rectangle corresponds to the region analysed by EBSD. The intermediate layer exhibits a well-defined, fine-grained microstructure with columnar grains.

The microstructure of the welding zone and the intermediate layer can be studied in even greater detail with a much higher magnification in the TEM. TEM bright field images of the welding zone are shown in figure 3. The seam is oriented in vertical direction. The difference between the intermediate layer and the initial microstructure is evident, so that the intermediate layer boundaries can be very simply emphasized with thin white lines and arrows, as depicted in figure 3(a). The small part of the welding seam studied here is fully bonded. The TEM micrograph again clearly shows that the microstructure of the intermediate layer consists of very fine grains and with a correspondingly high density of grain boundaries. In figure 3(b), another position along the weld is shown with higher magnification. Only one side of the intermediate layer is shown, and a sharp boundary can be observed between the intermediate layer and the region of initial material (associated with a much coarser grain size). Within the layer, the columnar grains seem to be grown from the boundary in the interface direction (white arrows indicate the potential growth direction in figure 3(b)).

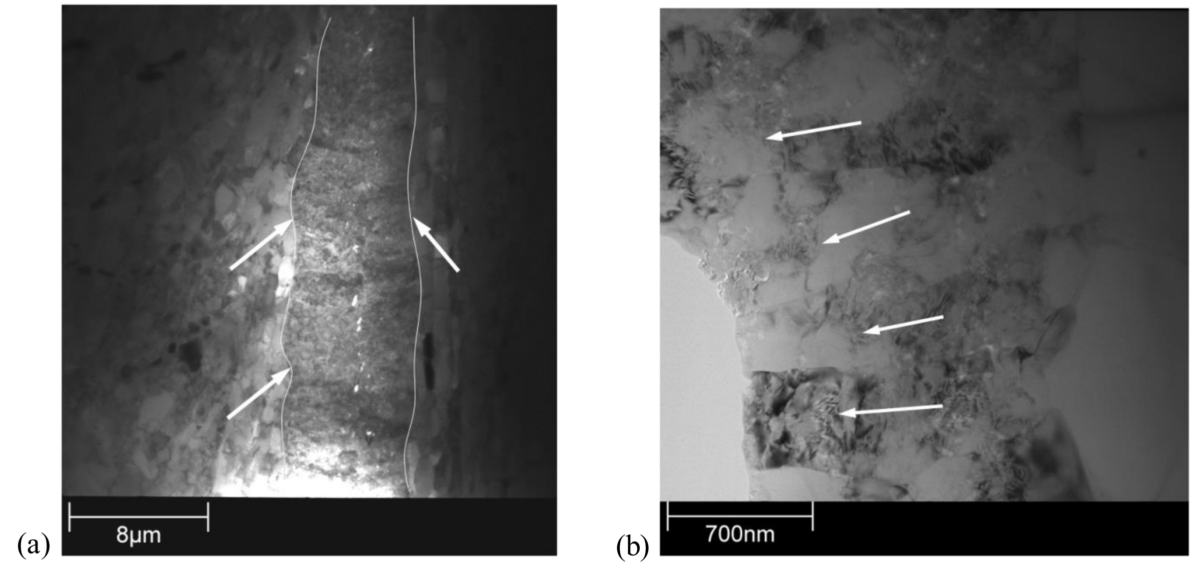


Figure 3. TEM bright field images of the intermediate layer. (a) The layer is highlighted by white lines and arrows. It exhibits a fine grain structure differing from the initial bulk grain structure. (b) One side of the intermediate layer (left) with grains in columnar form. The white arrows indicate the growth direction away from the coarse grained bulk material (right).

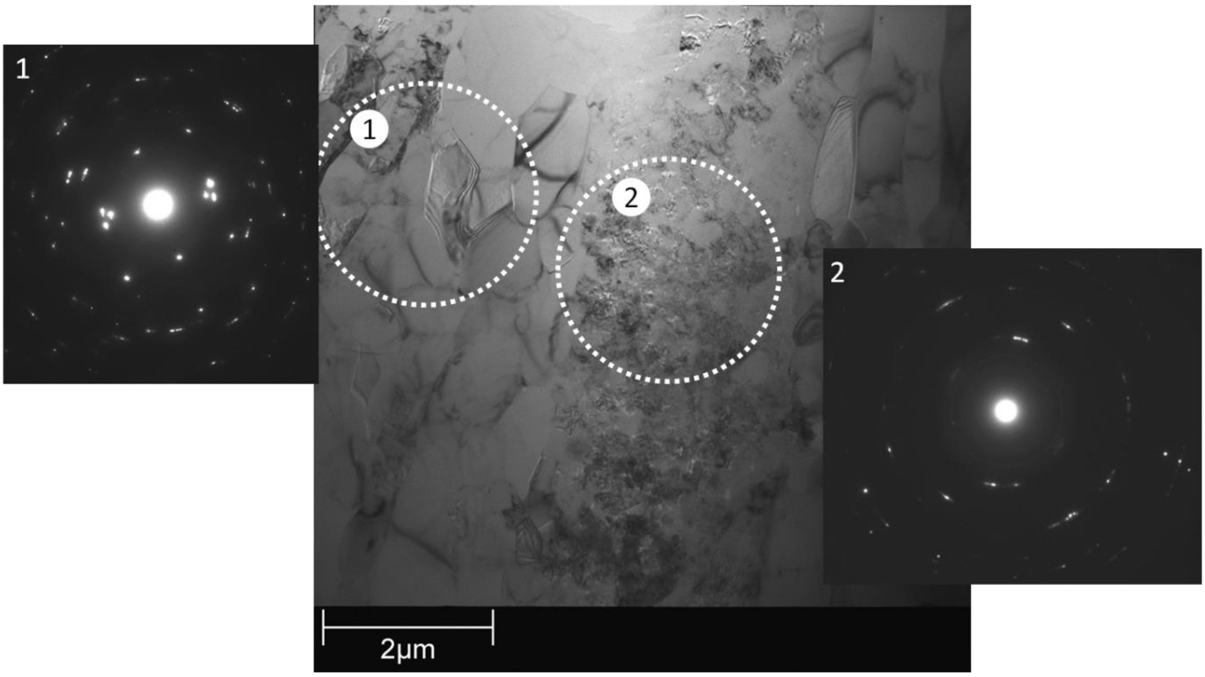


Figure 4. Bright field TEM image of the welding zone and SAED pattern of (1) thecoarse-grained near-interface region, and (2) the fine-grained intermediate layer. The low intensity of diffraction rings in (2) is due to the low thickness of the sample.

SAED patterns were recorded near the interface and inside the intermediate layer itself. Figure 4 shows the bright field TEM image; the regions where SAED patterns were recorded are highlighted by circles and the corresponding SAED patterns are shown on the left and right sides of figure 4, respectively. The first region (near-interface region) contains only a few coarse grains from the initial microstructure. The SAED pattern therefore only exhibits some individual diffraction spots. In contrast, the SAED image of the intermediate layer is characterized by blurred diffraction spots and by concentric rings. These features clearly indicate the fine-grained microstructure in the intermediate layer.

4. Summary and conclusions

The interfacial microstructure of the aluminum/aluminum joints fabricated by magnetic pulse welding was characterised using optical and electron microscopy, and in particular by EBSD (in the SEM) and SAED (in the TEM). While this brief report only highlights typical results from our on-going microstructural investigations of interface regions in joints produced by EMPW, we highlight that the EBSD measurements and the TEM investigations are in good agreement; they clearly demonstrate that an intermediate layer is formed during EMPW, and that this layer is characterized by microstructural features (fine, and partly columnar grains) that strongly differ from the initial bulk material that can also be observed in the vicinity of the newly formed weld zones. Our microstructural observations further indicate that the intermediate layer is formed by local melting and rapid crystallisation of the near-interface regions. This process is closely related to the high impact energies during EMPW, which are concentrated on a small material volume and may hence lead to a considerable increase in temperature. This, in turn, results in pronounced temperature gradients in the aluminum sheets that are likely to lead to columnar grain growth in the thin intermediate layer during subsequent, rapid crystallization. Obviously, the local behaviour of the intermediate layer plays an important role in providing good adhesive bonding in the EMPW joints.

Acknowledgements

This work was performed in project A8, cooperating with project A5, of the German Research Foundation’s (DFG) Priority Programme SPP 1640 “Joining by plastic deformation”.

5. References

[1] Groche P, Wagner M.F.-X, Pabst C, Sharafiev S 2014 Development of a novel test rig to investigate the fundamentals of impact welding *J. Mater. Process. Technol.* **214** 10 pp 2009-17

[2] Ben-Artzya A, Stern A, Frage N, Shribman V, Sadot O 2010 Wave formation mechanism in magnetic pulse welding *Int. J. Impact Eng.* **37** 4 pp 397–404

[3] Lee K.-J, Kumai S, Arai T, Aizawa T 2007 Interfacial microstructure and strength of steel/aluminum alloy lap joint fabricated by magnetic pressure seam welding *Mater. Sci. Eng.* A **471** pp 95–101

[4] Kapil A, Sharma A 2015 Magnetic pulse welding: an efficient and environmentally friendly multi-material joining technique *J. Cleaner Prod.* **100** 1 pp 35–38