IOP Conference Series: Materials Science and Engineering

Intermetallic layers in temperature controlled Friction Stir Welding of dissimilar Al-Cu-joints

To cite this article: R Marstatt *et al* 2018 *IOP Conf. Ser.: Mater. Sci. Eng.* **373** 012017

IOP Conf. Series: Materials Science and Engineering **373** (2018) 012017 doi:10.1088/1757-899X/373/1/012017

Intermetallic layers in temperature controlled Friction Stir Welding of dissimilar Al-Cu-joints

R Marstatt[1,*], M Krutzlinger[2], J Luderschmid[1], G Constanzi[2], J F J Mueller[1], F Haider[1] and M F Zaeh[2]

[1] Chair for Experimental Physics 1, University of Augsburg, Universitaetsstr. 1, 86159 Augsburg, Germany
[2] Institute for Machine Tools and Industrial Management (*iwb*), Technical University of Munich, Boltzmannstr. 15, 85748 Garching, Germany

[*] e-mail: roland.marstatt@physik.uni-augsburg.de

Abstract. Friction Stir Welding (FSW) can be performed to join dissimilar metal combinations like aluminium and copper, which is of high interest in modern production of electrical applications. The amount of intermetallic phases in the weld seam is significantly reduced compared to traditional fusion welding technologies. Because the solidus temperature is typically not reached during FSW, the growth of intermetallic phases is impeded and the intermetallic layer thicknesses typically remains on the scale of a few hundred nanometres. These layers provide a substance-to-substance bond, which is the main joining mechanism. Latest research confirms that the layer formation is most likely driven by the heat input during processing. Hence, the welding temperature is the key to achieve high quality joints. In this study, aluminium and copper sheets were welded in lap joint configuration using temperature-controlled FSW. An advanced in-tool measurement set-up was used to determine precise temperature data. Scanning electron microscopy (SEM) was used to analyse metallurgical aspects (e.g. structure and composition of the intermetallic phases) of the joints. The results show a correlation between the welding temperature and the thickness of the intermetallic layer and its structure. The temperature control significantly improved the correlation compared to previous studies. This leads to an enhanced understanding of the dominating joining mechanisms.

1. Introduction and state of the art

The recent changes in automotive design and construction require welding technologies, which are capable of joining dissimilar metals. One material combination of high importance in this regard is aluminium and copper. Both materials are widely used to produce efficient electrical powertrains. Friction Stir Welding (FSW) became an established process to join dissimilar materials [1]. The high electrical currents in automotive applications demand for high electrical conductivities within the connections of aluminium-copper joints.

The correlation between the welding parameters and the welding conditions on the one hand as well as the mechanical properties of the joints and their metallurgical structure on the other hand have been analysed in numerous studies. Detailed reviews concerning these cause-effect relationships were provided by [2–4].

The formation of layers of intermetallic compounds (IMC) has a significant influence on the joint properties. The layer thicknesses vary mostly due to the restrictions of the experimental set-up resulting in thermal effects such as heat accumulation for instance. Amongst others, the joint configuration, a tool offset and the parameter settings are the main influences on the process. The amount of IMCs decreases for an increasing feed rate and a decreasing rotational speed as reported by [5] for lap joints of aluminium 1060 and commercially pure copper. The authors suggested that neither low nor high heat input conditions result in sufficient joint strengths. The IMCs were observed near the workpiece interface within a region that was termed by the authors as black area. A reduced tensile strength for lap joints of aluminium Al5083 and commercially pure copper was concluded by [6]. This was ascribed to increased amounts of IMCs and micro cracks due to a high heat input. Several IMCs at different positions within cross sections of the seams for butt joints of aluminium AA2024-T3 and pure copper Cu10100 were detected [7]. Both studies did not specifically report a detailed analysis of the interface area. According to [8–14], an IMC layer is formed at the interface of the materials due to interdiffusion. Continuous IMC layers of about 1 μm thickness were observed for butt joints of aluminium 1060 and commercially pure copper [8, 9]. Similar results were reported for aluminium-copper butt joints (5A02 with T2 and AA1100-H14 with cp, respectively) [10, 11]. It was concluded that an excellent metallurgical bonding is achieved by very thin IMC layers leading to enhanced joint strengths. Butt joints of aluminium 1050 and commercially pure copper were welded by [12]. Here, the tool was only stirring in the aluminium. The authors detected a thin IMC layer of about 200 nm, which was supposed to form after the tool passed. Detailed analyses on the formation kinetics of the IMCs were performed by [13]. They reported layer thicknesses up to 4 μm for butt joints of aluminium 6082-T6 and pure copper. Since the layer was thicker than 2.5 μm, which was described as the upper limit to achieve a sufficient joint strength by [9], 4 μm could result in a reduced joint strength. However, the joint strength was not measured by [13] and the used materials from both studies differ significantly. The correlation between the welding temperature and the growth of the IMC layers for lap joints of aluminium EN AW-1050 and copper CW008A was analysed in [14]. Increasing the rotational speed led to increased and saturated welding temperatures. A similar trend was observed for the dependency between the rotational speed and the joint strength. The authors proved the thicknesses of the IMC layers (all below 1 μm) to correlate with the welding temperature via an Arrhenius law.

The formed IMCs were specified by selected area electron diffraction (SAED) in transmission electron microscopy (TEM). It was found by [9; 12; 13] that the IMCs contain the θ-phase (Al_2Cu) and the γ_2-phase (Al_4Cu_9). Although [12] and [13] only observed these phases, the η_2-phase (AlCu) as a third component was detected in [9]. The stoichiometry of the IMC double layer was analysed by [14] for a set-up that is comparable to the current study. Investigations based on energy-dispersive X-ray spectroscopy (EDS) suggested the formation of the phases AlCu and $AlCu_3$.

The electrical resistance of friction-stir-welded aluminium-copper joints was investigated by [15] and [16]. Increasing resistances were measured for increasing heat inputs whereas the rotational speed was kept constant for welding butt joints of AA5754 and CW11000 [15]. It was suggested that this could result from the formation of IMCs. However, experiments on lap joints of aluminium ASTM 6060 T5 and copper ASTM B110 were performed in [16]. The authors could not observe a significant influence of the rotational speed on the electrical resistance and concluded that there is no indication of a deleterious effect of formed IMCs on the electrical conductivity of the joints.

It is evident that the thickness of IMC layers significantly affects the mechanical and physical properties of friction-stir-welded joints. Hence, strategies to influence or even control the thickness are crucial to achieve tailored joint properties. One approach is to offset the probe from the materials' interface as suggested by [12] to maintain thin layers of about 200 nm. The formation of IMCs in butt joints of aluminium AA6082-T6 and copper Cu-DHP was inhibited by offsetting the tool in [17]. However, the mechanical properties of the joints were not improved. Another approach is to control the welding temperature as demonstrated by [18] for lap joints of aluminium EN AW-6082-T651 and copper CW008A on a FSW robot in force-controlled mode. A significantly reduced flash formation due to the controlled heat input was observed.

Summarizing the studies discussed above, the following conclusions can be drawn:

- FSW is suitable to join aluminium and copper.
- The formation of IMCs influences the joint properties.
- Thin IMC layers provide a strong metallurgical bonding.
- Tool offsetting prohibits mechanical intermixing and IMCs in the nugget.
- Temperature-controlled FSW facilitates a defined heat input.

2. Experimental and analytical set-up

The effects of temperature-controlled FSW on the thickness of IMC layers are discussed in this study. For this purpose, lap joints of aluminium and copper were produced with defined welding temperatures. The temperature control was achieved by a PI controller and combined with a position control during the process to ensure a defined distance between the probe tip and the interface of the materials.

2.1. Experimental set-up

The sample dimensions and the lap configuration of the aluminium-copper joints were defined according to [14] (see Figure 1). The aluminium sheets of the commercially pure alloy EN AW-1050 have dimensions of $245\ x\ 100\ x\ 4\ mm$ and the copper sheets of the commercially pure alloy CW008A $245\ x\ 100\ x\ 2\ mm$. The overlap length was set to $40\ mm$. The copper sheet was positioned on the retreating side (RS) and the aluminium sheet on the advancing side (AS) of the tool. The tool dimensions were $14\ mm$ for the shoulder diameter and $5\ mm$ for the conical probe ($3.6\ mm$ probe tip diameter). The probe length was applied to ensure only stirring in the aluminium sheet with a probe-tip-to-interface distance of $d_{PT-I} = 0.1\ mm$ for a tilt angle of 2° and a shoulder plunge depth of $0.1\ mm$. The tool probe was machined with three equally distributed flats and threaded. The experiments were performed on a CNC milling machine Heller MCH250.

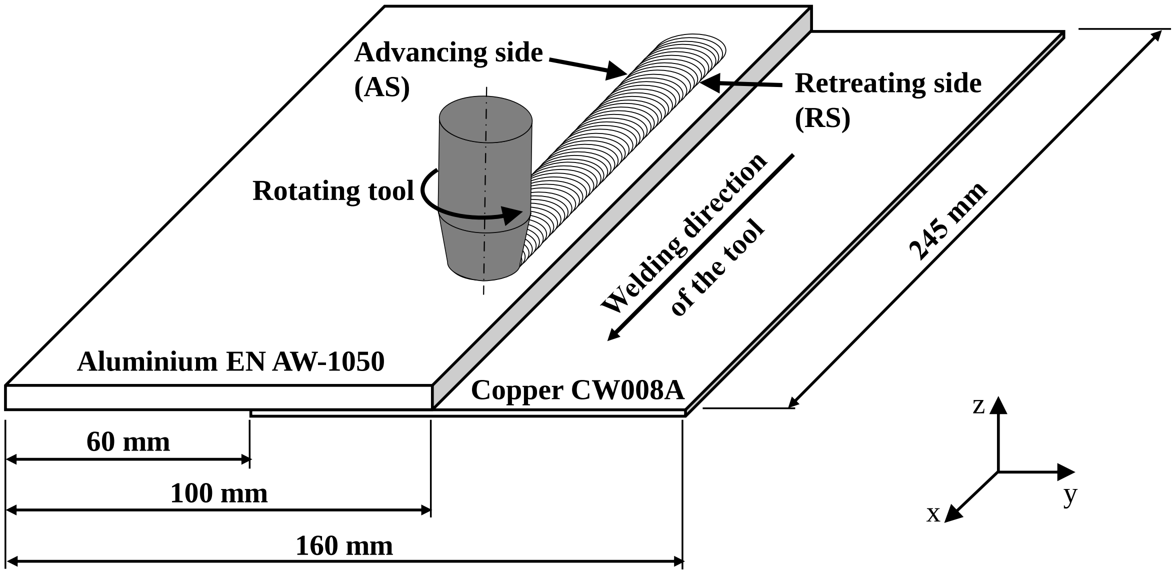

Figure 1. Schematic diagram of the sample dimensions and of the lap-welded aluminium-copper joints according to [14].

A closed-loop approach was used to implement a temperature-controlled FSW process. The controller system, which consists of the temperature measurement system according to [19], the PI controller and the milling machine, allowed to combine temperature as well as position control. The probe was equipped with a thermocouple of type K (diameter $0.5\ mm$) to measure the actual welding temperature during FSW (see Figure 2). Since the thermocouple was positioned at the middle of one flat and regarding the high thermal conductivity of the base materials, the interface temperature is assumed to almost equal the welding temperature. The PI controller calculated the required rotational speed n to adjust the welding temperature to the set temperature.

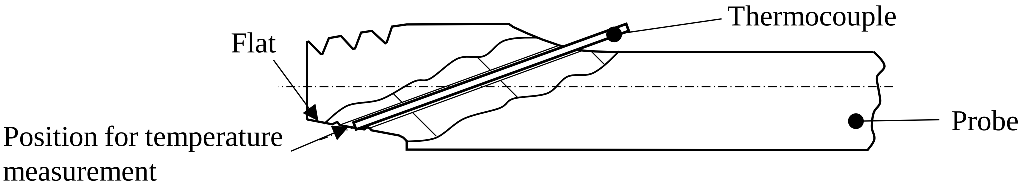

Figure 2. Position of the thermocouple to measure the welding temperature for temperature control.

The experiments were conducted for six different levels of the welding temperature; the lowest and highest temperature level were repeated (see Table 1). The boundaries of the welding temperature were defined based on experiments at constant rotational speeds of $n = 800\ min^{-1}$ and $n = 2800\ min^{-1}$ (see [14]). The feed rate was set to $v = 300\ mm/min$.

Table 1. Settings of the welding temperature for the experiments.

Sample	Welding temperature in $°C$
1	410
2	410
3	430
4	465
5	500
6	535
7	570
8	570

2.2. Analytical set-up

The specimens for analyses with scanning electron microscopy (SEM) were cut out perpendicular to the welding seam at $85\ mm$ and $135\ mm$ relative to the starting edges of the sheets. Grinding down to FEPA-P4000 and polishing with diamonds of $3\ \mu m$ and $1\ \mu m$ were conducted to prepare the specimens for the SEM. The final polishing was applied with a solution of SiO_2 nanoparticles and H_2O_2 in water. For the analyses, a ZEISS Merlin equipped with an Oxford EDS system was used.

3. Interface analysis

The investigation of the joining interface revealed the existence of interlayers consisting of two IMC phases. Figure 3 shows the SEM images of three interface areas welded at temperatures of $410\ °C$, $465\ °C$ and $540\ °C$. The layer thicknesses ranged within some hundred nanometres depending on the parameter settings. For the phase adjacent to copper, EDS analyses based on SEM using $4.5\ keV$ acceleration voltage resulted in a composition of $37.4\ at\%$ Al and $62.6\ at\%$ Cu. The phase layer next to the aluminium consisted of $64.0\ at\%$ Al and $36.0\ at\%$ Cu. The stoichiometries imply that the IMCs Al_4Cu_9 and Al_2Cu were formed, which was described in [9; 12; 13]. Since the analysis of nanolayers in SEM via EDS can be error-prone to a large extent, the IMCs could also be AlCu and/or $AlCu_3$. The formation of those IMCs was mentioned in other studies (e.g. [14]). TEM sample preparation of the interface by ion polishing is a challenging task. As all attempts lead to insufficient sample quality, distinct identification of the IMCs via TEM diffraction as conducted in [12] or [13] was not successful. Cutting electron transparent lamella by focused ion beam (FIB) is planned for the future.

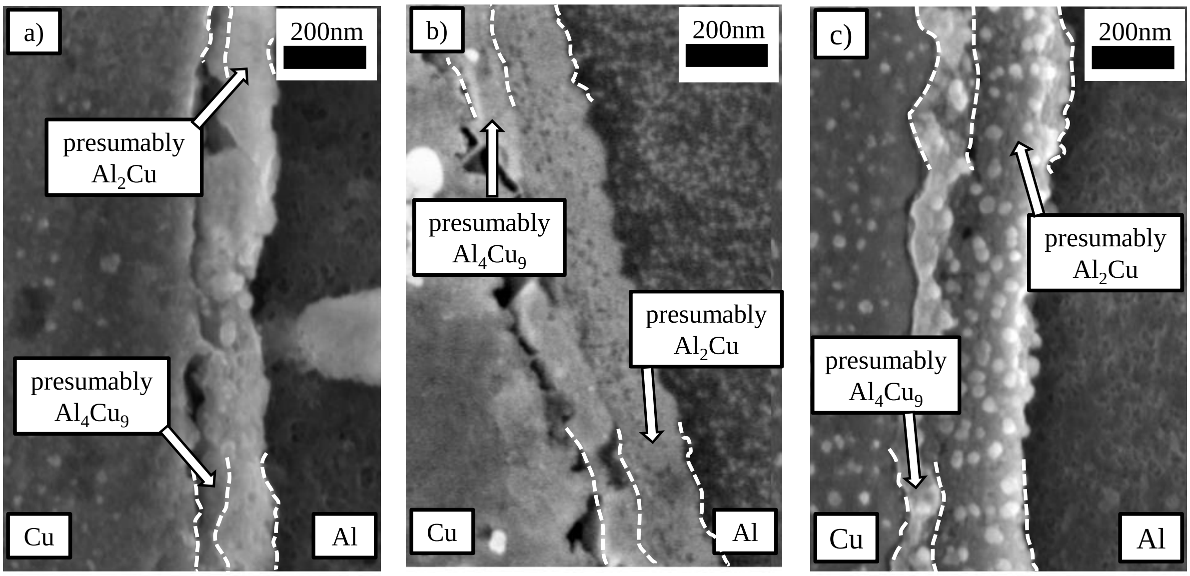

Figure 3. SEM images of the interface at a) $410\ °C$, b) $465\ °C$ and c) $540\ °C$ nominal temperature.

To gather valid information on the thickness of the IMC layers, the SEM specimens were measured at different positions of the cross section. Thus, a sound mean value and the standard deviation of the layer thickness for each parameter setting could be derived. Figure 4 shows the measured layer thicknesses drawn logarithmically against the inverse temperature in units of K. The margins surrounding the mean values are the standard deviations of the respective measures. A linear behaviour is clearly visible in this Arrhenius plot.

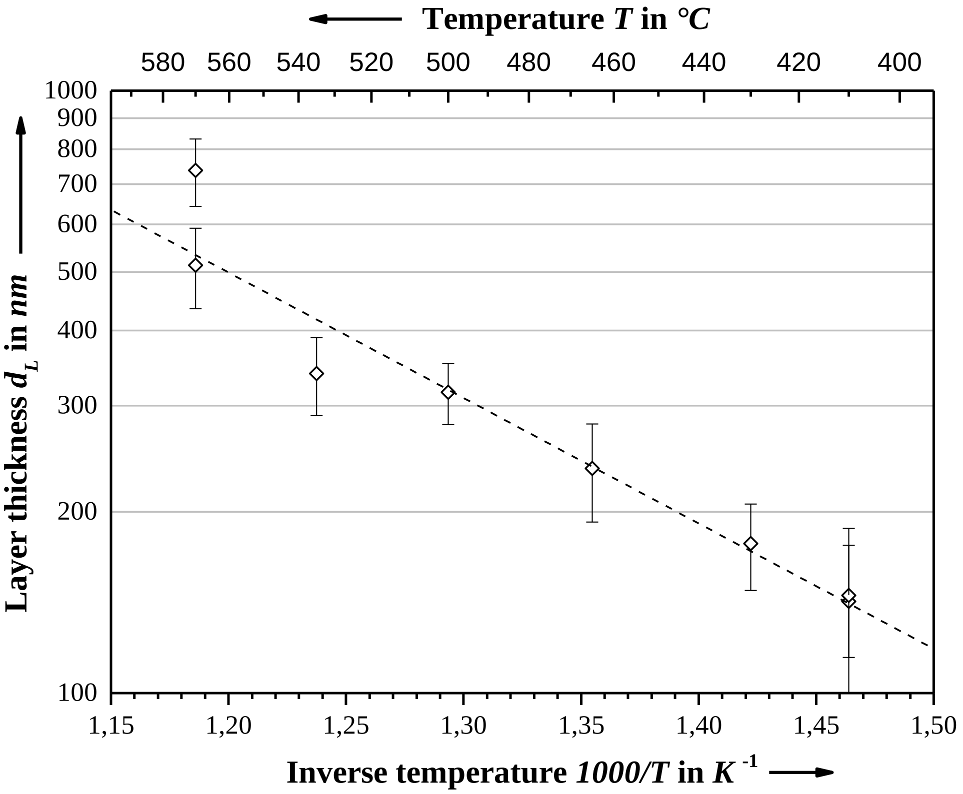

Figure 4. Arrhenius plot of welding temperature dependent doublelayer thickness.

The thickness $d(t)$ of the intermetallic layers grows by interdiffusion according to

$$d(t) = \sqrt{2Dt}, \tag{1}$$

where t is the time of diffusion and D is the rate constant of diffusive layer growth. The growth process is assumed to be thermally activated as

$$D(T) = D_0\, e^{-\frac{E_{act}}{k_B T}}. \tag{2}$$

T is the temperature, E_{act} the activation energy, D_0 is the prefactor of diffusion and k_B the Boltzmann constant. Combining equations (1) and (2) yields

$$ln(d) = \frac{1}{2} ln\left(2t_{eq}D_0\right) - \frac{E_{act}}{2k_B}\frac{1}{T_{weld}}\ . \tag{3}$$

Here, T_{weld} is the controlled welding temperature and t_{eq} is the equivalent time interval around the peak of the temperature, which occurs during welding.

The slope of the linear fit from Figure 4, results in an activation energy of $E_{act} = 0.84 \pm 0.05\ eV$ for the growth of the double layer. The intermetallic layer growth by interdiffusion between Al and Cu was investigated by [20]. The resulting activation energies were specified to range from $0.85\ eV$ to $2.65\ eV$. An activation energy of $E_{act} = 1.27\ eV$ for the growth of Al_2Cu and $E_{act} = 1.37\ eV$ for the growth of Al_4Cu_9 was determined. The experiments of [20] were conducted using annealed material. Accordingly, it has to be considered that the activation energy can be reduced by about one third. This is due to vacancy supersaturation or short circuit diffusion along dislocations or grain boundaries in highly deformed friction-stir-welded nugget material. An activation energy of $2.33\ eV$ could be measured in [14] for a comparable welding setup considering the investigated temperatures obtained in the heat affected zone (HAZ). Hence, the nugget temperatures in this study are more than $150\ K$ higher than the temperatures in [14]. The temperatures measured in the HAZ seem to be suitable for both process observation and identifying a suitable set of parameters. For a detailed understanding, a profound knowledge of the temperature of the nugget as recorded in this study is needed. The intercept of the straight line fitted in Figure 4 results in $t_{eq} * D_0 = 1.57 \cdot 10^{-4}\ cm^2$. Assuming t_{eq} to be in the order of a few seconds (as done in [14]), this corresponds to D_0 of about $10^{-5}\ cm^2/s$, which is in good agreement to the findings in [20].

4. Conclusions and outlook

Dissimilar aluminium-copper lap joints were welded using temperature-controlled FSW. The thickness of the IMC layer at the interface was analysed using electron microscopy. Regarding the discussed results, the following conclusion can be drawn:

- The observation of an Arrhenius behaviour of the growth of the intermetallic layer was found, which is in agreement with previous studies by [14].
- An improved measurement system compared to [14] enabled to measure and control the welding temperature precisely. The interface temperature is assumed to almost equal the welding temperature. Therefore, an adapted Arrhenius analysis provides results, which are comparable and consistent to data of diffusion processes known from literature.
- A temperature control during FSW based on an in-tool temperature measurement combined with the derived Arrhenius correlation of welding temperature and IMC layer thickness offers new potential for joining dissimilar materials. The thickness of the IMC layer can be controlled precisely even for complex geometries and tailored to individual requirements.

5. References

[1] Murr L E 2010 A Review of FSW Research on Dissimilar Metal and Alloy Systems *J. Mat. Eng. and Perform.* **19** 1071–89

[2] Mubiayi M P and Akinlabi E T 2013 Friction Stir Welding of Dissimilar Materials between Aluminium Alloys and Copper - An Overview *World Acad. Sci., Eng. and Techn.* **76** 633–8

[3] Mehta K P and Badheka V J 2015 A Review on Dissimilar Friction Stir Welding of Copper to Aluminum: Process, Properties, and Variants *Mat. and Manuf. Proc.* **31** 233–54

[4] Galvão I, Loureiro A and Rodrigues D M 2016 Critical review on friction stir welding of aluminium to copper *Sci. and Tech. Weld. and Join.* **21** 523–46

[5] Abdollah-zadeh A, Saeid T and Sazgari B 2008 Microstructural and mechanical properties of friction stir welded aluminum/copper lap joints *J. All. and Comp.* **460** 535–8

[6] Bisadi H, Tavakoli A, Tour Sangsaraki M and Tour Sangsaraki K 2013 The influences of rotational and welding speeds on microstructures and mechanical properties of friction stir welded Al5083 and commercially pure copper sheets lap joints *Mat. & Des.* **43** 80–8

[7] Carlone P, Astarita A, Palazzo G S, Paradiso V and Squillace A 2015 Microstructural aspects in Al–Cu dissimilar joining by FSW *Int. J. Adv. Manuf. Technol.* **79** 1109–16

[8] Xue P, Xiao B L, Ni D R and Ma Z Y 2010 Enhanced mechanical properties of friction stir welded dissimilar Al–Cu joint by intermetallic compounds *Mat. Sci. and Eng.:* A **527** 5723–7

[9] Xue P, Xiao B L and Ma Z Y 2015 Effect of Interfacial Microstructure Evolution on Mechanical Properties and Fracture Behavior of Friction Stir-Welded Al-Cu Joints *Met. and Mat. Trans.* A **46** 3091–103

[10] Tan C W, Jiang Z G, Li L Q, Chen Y B and Chen X Y 2013 Microstructural evolution and mechanical properties of dissimilar Al–Cu joints produced by friction stir welding *Mat. & Des.* **51** 466–73

[11] Muthu M F X and Jayabalan V 2015 Tool travel speed effects on the microstructure of friction stir welded aluminum–copper joints *J. Mat. Proc. Tech.* **217** 105–13

[12] Genevois C, Girard M, Huneau B, Sauvage X and Racineux G 2011 Interfacial Reaction during Friction Stir Welding of Al and Cu *Met. and Mat. Trans.* A **42** 2290–5

[13] Avettand-Fenoël M N, Taillard R, Ji G and Goran D 2012 Multiscale Study of Interfacial Intermetallic Compounds in a Dissimilar Al 6082-T6/Cu Friction-Stir Weld *Met. and Mat. Trans.* A **43** 4655–66

[14] Marstatt R, Krutzlinger M, Luderschmid J, Zaeh M F and Haider F 2017 Formation of a diffusion-based intermetallic interface layer in friction stir welded dissimilar Al-Cu lap joints *IOP Conf. Ser.: Mater. Sci. Eng.* **181** 12002

[15] Akinlabi E T, Madyira D M and Akinlabi S A 2011 Effect of Heat Input on the Electrical Resistivity of Dissimilar Friction Stir Welded Joints of Aluminium and Copper *IEEE Africon 2011 (Livingston, Zambia)* (New York: IEEE)

[16] Wiedenhoft A G, Amorim H J, Rosendo T S and Strohaecker T R 2016Friction Stir Welding of Dissimilar Al-Cu Lap Joints with Copper on Top *KEM* **724** 71–6

[17] Galvão I, Loureiro A, Verdera D, Gesto D and Rodrigues D M 2012 Influence of Tool Offsetting on the Structure and Morphology of Dissimilar Aluminum to Copper Friction-Stir Welds *Met. and Mat. Trans.* A **43** 5096–105

[18] Bachmann A, Gamper J, Krutzlinger M, Zens A and Zaeh M F 2017 Adaptive model-based temperature control in friction stir welding *Int. J. Adv. Manuf. Technol.* **93** 1157–71

[19] Costanzi G, Bachmann A and Zaeh M F 2017 Entwicklung eines FSW-Spezialwerkzeugs zur Messung der Schweißtemperatur (‚Development of a FSW tool to measure the welding temperature’) *DVS Berichte* vol 337 (Duesseldorf: DVS Media GmbH) 119–25

[20] Funamizu Y and Watanabe K 1971 Interdiffusion in the Al-Cu System *Trans. JIM* **12** 147–52

Acknowledgements

The research project “Mechanisms in joining of dissimilar materials by friction stir welding” is part of the priority program 1640 (SPP1640) “Joining by plastic deformation”, which is funded by the German Research Foundation (DFG). The authors would like to thank for the funding and the support. The authors also thank Andreas Bachmann from the Institute for Machine Tools and Industrial Management (*iwb*) of the Technical University of Munich for technical assistance concerning the temperature control of FSW.