Linear friction welding of aluminium to copper

I. Bhamji¹, R. J. Moat², M. Preuss^{*1}, P. L. Threadgill³, A. C. Addison⁴ and M. J. Peel⁵

The joining of dissimilar materials is attaining increasing importance as there is a drive to utilise hybrid structures and reduce the weight or cost of products. The present work therefore studied the linear friction welding of commercially pure grades of aluminium to copper (AA 1050 to C101) for potential power transmission applications. Results showed that welds with very good mechanical and electrical properties can be produced. The weld microstructure was analysed using optical microscopy, backscattered scanning electron microscopy, hardness testing and high energy synchrotron X-ray diffraction. These techniques were used in order to identify any cross-weld grain size variations and possible formation of intermetallic phases close to the weld line.

Keywords: Linear friction welding, Dissimilar materials, Aluminium, Copper

Introduction

Linear friction welding (LFW) is a solid state joining process that is currently being used commercially for producing integrally bladed disc (blisk) assemblies in aeroengines¹ and is under development for other applications.² The process may also be viable for the production of high strength dissimilar welds, and the present work concerns the LFW of aluminium (AA 1050-H111) to copper (C101), which has industrial relevance for power transmission applications. In view of the proposed final application, commercially pure grades of aluminium and copper, which give the best electrical conductivity, were used.

The ratio of conductivity to density is about two times greater for aluminium relative to copper, and therefore, aluminium is an attractive choice when weight is a design consideration (e.g. overhead power lines). However, when weight is not an important consideration, copper, which has higher absolute conductivity relative to aluminium, is usually the better option. Therefore, a method of joining aluminium to copper should allow a more optimised design solution for power transmission systems. The lower cost of aluminium relative to copper also means that it would be attractive to replace certain copper parts of power transmission systems with aluminium where appropriate.

The aim of this work was to demonstrate the feasibility of joining aluminium to copper by LFW for proposed applications in power transmission systems. Two of the key properties for such welds will be weld

strength and electrical resistivity across the joint, and both of these aspects were investigated in this study. The objective of this work was to develop welding parameters that would give weld mechanical and electrical properties comparable to those of the parent aluminium (the parent aluminium was mechanically weaker and less electrically conductive than the parent copper).

As aluminium–copper welds for power transmission applications are likely to be functional rather than structural, electrical rather than mechanical properties are likely to be of greater importance. The microstructure is known to affect electrical properties with smaller grain sizes (increased volume fraction of grain boundaries), increased solute concentrations and increased lattice defects (dislocations), increasing resistivity.³ All of these entities act as scattering centres and therefore impede the flow of current across the sample. A further factor which increases resistivity is the sample temperature, with higher sample temperatures increasing lattice vibrations and therefore increasing scattering.

Another factor which can significantly increase the sample resistivity is the presence of a layer of intermetallic at the weld interface. Aluminium–copper intermetallics have much higher resistivity than either of the parent metals (Table 1), and therefore, the presence of these intermetallics could cause excessive resistance and unwanted heating at the weld line. This could be important as there are requirements for bus bars to be kept below certain temperatures during operation (BS 159:1992).

Although LFW is a promising process for joining dissimilar metals, very little information on this subject is available in the public domain. A few reports have discussed the LFW of aluminium (AA 6063) to oxygen free copper,^{7,8} and it was found that welds with good electrical properties could be produced. However, no details of the mechanical properties of these welds were reported. Linear friction welds were compared with those produced by explosive welding, and it was found

¹Manchester Materials Science Centre, University of Manchester, Grosvenor Street, Manchester M1 7HS, UK

²The Open University, Milton Keynes MK7 6AA, UK

³Formerly with TWI Ltd, Cambridge, UK (now retired)

⁴TWI Ltd, Cambridge, UK

⁵University of Bristol, Queens Building, University Walk, Bristol BS8 1TR, UK

*Corresponding author, email Michael.Preuss@manchester.ac.uk

that the linear friction welds had a much reduced amount of intermetallic phase formation in the weld region.^{7,8} Despite the significantly reduced level of intermetallic formation, however, the as welded conductivities of the samples were very similar to those produced by explosive welding.⁷

Rotary friction welding is a competing technology for the welding of aluminium to copper, and welds with high strength can be produced using this process.^{9,10} However, rotary friction welding is only suitable for the welding of axisymmetric parts, while LFW can also be used to weld non-axisymmetric parts. Good welds can also be produced using laser welding (AA 4047 to an oxygen free copper)¹¹ and explosive welding.¹²

Experimental

Materials and welding process set-up

Attempts were made to weld samples of geometry $50 \times 12 \times 50$ mm with a weld interface of 50×12 mm. AA 1050-H111 (Fe, 0.4 wt-%; Mg, <0.1; Si, <0.1; Mn, <0.1; Al, balance) and C101 (Cu alloys with no deliberate alloying additions) alloys were used for the welding trials. Welds were produced on an electro-mechanical LFW machine² based at TWI in Cambridge, UK.

The aluminium sample was reciprocated in the 50 mm dimension for welding, while the copper sample was held stationary. Before welding, the welding faces were milled and degreased with acetone. The process parameters that were varied in this study were frequency of oscillation, amplitude of oscillation and friction pressure. A forge pressure of 75 MPa was used, which was applied for a period of 5 s. A burn-off distance of 2 mm was used in most cases; however, this was changed slightly in certain circumstances (please see Ref. 1 for detailed definitions of welding parameter terms). Initial parameters were derived from past experience of welding similar materials at TWI Ltd using linear and rotary friction welding.

Mechanical properties

Weld mechanical properties were characterised by tensile and hammer bend tests. Tensile tests were conducted in accordance with BS EN 1002-1:2001. Hammer bend tests (BS EN ISO 15620:2000), where one side of the weld (copper half) was held in a vice and the other (aluminium half) subjected to hammer blows until some plastic deformation of the impacted half of the weld, were also conducted on a few samples. A pass on this test would be some plastic deformation of the impacted half of the weld before failure. Experience has shown that this is a good test of weld quality in friction

welds (BS EN ISO 15620:2000). Weld flash was machined away before hammer bend testing.

Microstructure characterisation

Optical microscopy, backscattered scanning electron microscopy (SEM) and synchrotron X-ray diffraction techniques were used to analyse the weld microstructure. Optical microscopy was applied to analyse changes in grain size across the weld, while the other techniques were used to generally analyse the weld microstructure and to determine if intermetallics were present at the weld interface. For optical microscopy, the aluminium half of the weld was electrolytically etched in Barkers reagent (11.5 mL fluoroboric acid, 1.75 g boric acid and 24.2 mL water), while the copper half was electrolytically etched in sulphuric acid.

A cross-weld Vickers microhardness trace was completed for one weld. The test was conducted with a load of 200 g and a loading time of 10 s. In order to obtain close spacings between hardness indents, a diagonal path was utilised. The distance between indents was always at least three times the indentation size, and all hardness indents were made in the middle two-thirds of the weld. Slight variations in hardness parallel to the weld line may be expected in these welds, but these variations are likely to be minor relative to variations across the weld line.

High energy synchrotron X-ray diffraction, conducted at the European Synchrotron Radiation Facility, Grenoble, France, was used to detect and quantify the amount of intermetallic phases present at the weld interface. Experiments were undertaken in transmission so that the incident beam passes through the sample and the diffraction rings are collected by a two-dimensional detector on the other side of the sample. The sample was cut to ~ 2 mm thickness to allow the experiment to be conducted in transmission. A monochromatic beam of wavelength $0.142 \text{ \AA}$ (88 keV) and $200 \times 200 \text{ }\mu\text{m}$ cross-section was used to obtain diffraction patterns from locations along a line going across the weld line at mid width. A step size of $100 \text{ }\mu\text{m}$ was applied, which resulted in overlapping diffracting gauge volumes. A high resolution Pixium 4700 area detector, placed 646 mm away from the sample, was used to collect the complete Debye Scherrer diffraction rings. With the given energy/sample detector distance, it was possible to record a number of different diffraction rings at the same time. Since each measurement point only took ~ 10 s, it was possible to produce a very detailed and complete map of microstructure across the weld line in less than an hour. Data from the diffraction experiment were subsequently analysed in the software package MAUD,¹³ which utilises the Rietveld method.

Resistivity measurements

In order to characterise the resistivity of aluminium-copper welds, a 400 A direct current (dc) was passed through a welded sample that was machined down to 4.5×12 mm in cross-section (7.4 A mm^{-2}). In order to pass the current, a Union Carbide Linde type HDA-300 welding power supply unit was used. Flexible welding cables were bolted onto the welding unit via crimp terminals, with the crimp terminals on the other ends of the cables attached to either side of the workpiece using G clamps (Fig. 1). The potential difference across the weld was measured at various distances using a sensitive

Table 1 Resistivities of Al-Cu intermetallic phases and those of copper and aluminium⁴⁻⁶

Phase	Resistivity/ $\mu\Omega \text{ cm}$
Cu ₂ Al	14.2
Cu ₃ Al ₂	13.4
Cu ₄ Al ₃	12.2
CuAl	11.4
CuAl ₂	8
Cu (C101)	1.71
Al (AA 1050)	2.9

1 Schematic diagram of resistivity testing set-up used to test linear friction welds

multimeter. One of the multimeter probes was kept at a fixed far field location, and measurements were taken at 2.5 mm steps until the second probe was at a far field location on the other side of the weld line.

To prove the significance of the resistivity results, some finite element models were run in ABAQUS/Standard using a transient coupled thermal–electric procedure. The regions where microstructural changes occurred in the discussed linear friction welds were very small in size, which may have meant that any resistivity changes caused by these regions could not be detected with the resolution of the measurement techniques. The models were therefore used to determine whether these regions of microstructural change would have any practical impact if the welds were in operation.

The models consisted of a three-dimensional part, which was split into different sections with different material properties. The overall dimensions of the part were $200 \times 12.7 \times 6.35$ mm, and electric potential boundary conditions were applied to the two 12.7×6.35 mm faces, on either end of the part, to allow a potential difference and current flow across the part. Convection conditions were applied to all exposed surfaces of the part with a film coefficient of $10 \times 10^{-6} \text{ W mm}^{-2} \text{ }^{\circ}\text{C}^{-1}$ and a sink temperature of 20°C used. The analysis was set to terminate when the temperature change in an increment was $<0.1^{\circ}\text{C}$, i.e. when the analysis had reached steady state. Automatic incrementation was used with an initial increment size of 1 s. However, in all of the models, this had increased to 5 s, the set maximum, after only a few increments. The material properties specified in Table 2 were used.

The following three different situations were modelled:

- (i) no intermetallics: The part is split into two sections, with one section having material properties corresponding to copper and the other having properties corresponding to aluminium
- (ii) intermetallics: The part is split into three sections corresponding to copper, aluminium and a section of aluminium–copper intermetallic in between. The type of intermetallic and layer

thickness was derived from microstructure examination

- (iii) microstructure effects: The part is split into four sections corresponding to parent copper, process affected copper, process affected aluminium and parent aluminium. The size of these sections was again derived from microstructure examination. The resistivities of the process affected copper and aluminium regions were increased to a value that would allow a change in resistivity, relative to a part without high resistivity zones, to be detected using the current instrumentation. This was used as a check to determine whether a non-detectable change in resistivity, in material close to the weld line, would cause a significant increase in the operation temperature of the weld. Material properties in the process affected zones were kept the same as those of the parent materials, aside from the increased resistivity.

The three models were studied to determine the impact of the different zones on the temperature of the part when a potential difference is applied. This is significant as the maximum current that can be passed through a bus bar is determined by its intended temperature rise.¹⁴ In order to keep the current flowing through the part constant (at 400 A; this is a typical maximum current for bus bars of 12.7×6.35 mm cross-section¹⁵), in each model, the potential difference was adjusted. If the overall resistance of the part is increased in a particular model, by including high resistivity intermetallic layers, for instance, the potential difference also needs to be increased to allow the same current to flow through the part.

Results and discussion

Mechanical properties

A total of 11 welds were made using a range of conditions, as shown in Table 3. All of the welds seemed well formed from visual examination with ample flash coming from the aluminium half of the weld. Little or no flash came from the copper half of the weld (Fig. 2). This is to be expected as copper will be significantly stronger than aluminium at the welding temperature and therefore aluminium will deform preferentially to copper.

A total of four tensile tests were carried out on three welds (S1, S10 and S11), and each showed failure in the parent material well away from the weld line (Fig. 3 and Table 3). This suggests that the weld region had a higher ultimate tensile strength than the parent aluminium.

Hammer bend tests were conducted on four samples. Weld S3 performed well in this test, achieving a bend of $\sim 80^{\circ}$ without weld fracture (Fig. 4). Welds S5 and S6 also performed well with bends of 60 and 20° respectively

Table 2 Material properties for modelling resistive heating of aluminium–copper welds^{5,6,16,17}

Material	Thermal conductivity/ $\text{W mm}^{-1} \text{ }^{\circ}\text{C}^{-1}$	Density/ kg mm^{-3}	Electrical conductivity/ $\Omega^{-1} \text{ mm}^{-1}$	Joule heat fraction	Specific heat/ $\text{J kg}^{-1} \text{ }^{\circ}\text{C}^{-1}$
Aluminium	0.227	2.71×10^{-6}	34483	1	900
Copper	0.383	8.89×10^{-6}	58479	1	385
CuAl_2	0.13	4.36×10^{-6}	12500	1	710
Process affected aluminium	0.227	2.71×10^{-6}	19157	1	900
Process affected copper	0.383	8.89×10^{-6}	32468	1	385

2 Example of aluminium (top) to copper (bottom) linear friction weld

before some fracture at the weld line. It should be noted, however, that the test sample from S6 (dimension: $20.7 \times 11.3 \times 73.7$ mm) was much narrower than from S5 ($29.9 \times 11 \times 74.7$ mm), which may have had an effect on the stresses generated during the testing process. These results clearly show that welds with satisfactory mechanical properties can be produced by LFW.

Microstructure

Examination of the weld microstructure (Fig. 5) showed intimate contact between the two materials with no readily apparent flaws (e.g. voids, cracking, etc.). It is also clear from the high magnification backscattered SEM image (Fig. 5b) that no large layers of intermetallic are present at the weld interface. However, intermetallics could be present in small layers or as discontinuous particles, which are hard to detect from backscattered SEM images.

Synchrotron X-ray diffraction was used to determine if intermetallic phases were present at the weld line of an aluminium–copper weld (S2). Results showed small peaks corresponding to the CuAl_2 phase (Fig. 6a). A quantitative analysis conducted in MAUD, with the fit shown in Fig. 6a, suggested an intermetallic weight fraction of 0.5% was present. If all of these phases are free of preferred orientation and are concentrated in a continuous flat layer at the weld line, then this would correspond to a layer thickness of $\sim 0.7 \mu\text{m}$. From consideration of Fig. 5b, this seems quite large; however, it should be noted that, particularly for S2, there were a large amount of copper particles in the aluminium half of the weld (Fig. 6b). Thin intermetallic films around

3 Tensile specimen of aluminium (right) to copper (left) weld (S1)

these particles may also have contributed to the strength of the CuAl_2 diffraction peaks.

Optical microscopy was used to analyse differences in grain size across the welded sample. A refined grain structure is generally present close to the weld line of friction welds as the heavy deformation and heating cause recrystallisation, and the short welding time and high cooling rates do not allow significant growth of these recrystallised grains. Figure 7a shows that there has been a significant influence of the welding process on the microstructure of the aluminium close to the weld line. A heavily deformed microstructure is present over ~ 1.7 mm, and the grain structure is completely lost in a zone ranging $\sim 500 \mu\text{m}$ from the weld line. There may be some refinement of the microstructure in this zone. Similarly, there was a thin band of deformed material, $\sim 30 \mu\text{m}$ in width, close to the weld line in the copper half of the weld (Fig. 7b).

A hardness trace across the weld line showed that the hardness increases close to the weld line in both aluminium and copper (Fig. 8). A hardened zone ~ 1.4 mm in width was present in aluminium, while a 0.6 mm hardened zone was present in the copper close to the weld line. The width of the hardened zone in aluminium corresponds reasonably well with the heavily deformed zone seen in optical micrographs. However, the hardened zone in copper is far larger than the deformed zone seen from microscopy. This suggests that some strain hardening of the copper material, which is not detectable by simple optical microscopy, had taken place close to the weld line during welding.

Electrical resistivity

Electrical resistivity was tested in three welds (S4, S6 and S7), and for all tested welds, multimeter measurements showed that the potential difference increased linearly with distance, and there was no significant step increase in potential difference when measuring across the weld line (Fig. 9).

With the discussed resistivity measurements, it should be noted that an increase in resistance solely because of

Table 3 Welding parameters for LFW of aluminium to copper

Weld	Pressure/MPa Friction/forging	Frequency/ Hz	Amp/ mm	Burn-off/ mm	Tensile strength/MPa	Gauge diameter/mm	Bend	Comments
S1	75/75	50	2	1	76	8		Failure in parent Al
S2	75/75	50	2	1				
S3	75/75	50	2	2			Pass	Bend of $\sim 80^\circ$
S4	75/75	50	2	2				
S5	50/75	50	1.4	2			Pass	Bend of $\sim 60^\circ$
S6	50/75	50	1.4	2			Pass	Bend of $\sim 20^\circ$
S7	75/75	50	1.4	2			Fail	
S8	50/75	50	1.4	2				
S9	50/75	50	1.4	2				
S10	50/75	50	1.4	2	76	8		Failure in parent Al
S11	50/75	50	1.4	2	76 and 77	8		Two tensile tests from same weld; in both cases, failure in parent Al

a side view of bend test sample and b back view of bend test sample

4 Hammer bend test of aluminium to copper weld (S3)

5 Backscattered SEM images of aluminium (bottom) to copper (top) weld (S4): figures show intimate contact between two materials and no very large layers of intermetallic at weld interface

intermetallic layers is very hard to detect due to the very small thicknesses of these layers (certainly $<1\text{ }\mu\text{m}$). The potential difference due to a $1\text{ }\mu\text{m}$ thick layer of CuAl_2 is $0.6\text{ }\mu\text{V}$, which is far smaller than the detection range of the current set-up.

Similarly, microstructure changes (grain size and deformation), which are known to affect sample resistivity,³ only occur over $\sim 2\text{ mm}$ in these welds,

which may again mean that resistivity variations as a result of microstructural changes are hard to detect. A change in potential difference of $\sim 0.2\text{ mV}$ can be resolved with the current set-up. If a potential difference is measured over a 5 mm distance across the weld line, and it is assumed that there is 1.4 mm of deformed aluminium and 0.6 mm of deformed copper (widths derived from hardness measurements) close to the weld

6 a synchrotron X-ray diffraction trace from weld line of S2 showing peaks for Cu, Al and CuAl_2 and b backscattered SEM image of S2 showing copper particles flowing distance into aluminium: intermetallic films around these particles may have contributed to peaks seen in diffraction trace

a structure of aluminium close to weld line (weld line at very bottom of image); *b* structure of copper close to weld line (weld line towards top of image)

- 7 Optical micrographs of aluminium to copper weld (S9): there appears to be more refined grain structure in 500 µm zone close to weld line in *a*, while there is narrow deformed zone in *b*

line, then the resistivity of these deformed zones would need to be increased by 80%, relative to the parent materials, for a change to be detected. As this is a large resistivity change, it was important to determine if zones with an 80% increase in resistivity significantly affect the resistive heating of bus bars. The ABAQUS models were used to determine this. Although changes in electrical properties due to microstructure variations are hard to detect using the current methods, it should be noted that changes because of defects or poor weld quality should be detectable.

- 8 Hardness trace across aluminium to copper linear friction weld

- 9 Plots of potential difference against probe distance for S4: there is no noticeable step increase in resistivity at weld line

Three ABAQUS models were developed. The first model was a baseline model, which consisted of one part separated into equal dimension sections of aluminium and copper. A potential difference of 22.9 mV was applied across the sample to allow a current flow of 400 A. The second model included a 1 µm CuAl₂ layer in between aluminium and copper. The same potential difference (22.9 mV) was applied across the sample because of the very small increase in resistance, of the overall part, as a result of the intermetallic layer. Figure 10 shows that there is no difference in temperature between the part with and without intermetallics, and the traces lie exactly on top of one another.

The third model consisted of sections corresponding to copper and aluminium, but with zones of 1.4 mm in length in aluminium and 0.6 mm in length in copper, which had resistivities increased by 80%, relative to the parent materials (keeping all the other material properties constant). This model was used to determine if a resistivity increase that could not be detected with the experimental set-up could have a significant impact on the operation temperature of the weld. A potential difference of 23.1 mV was applied across the part to allow the current flow to remain at 400 A with the increased resistance. No intermetallic layer was included in this model as its presence made little difference,

- 10 Modelling results showing temperature profiles as result of resistive heating in part containing no intermetallics, part containing 1 µm layer of CuAl₂ and part including deformed zones that may cause increase in resistivity relative to that in parent materials

relative to the baseline, in the second model. There was a marginal increase in temperature in this model relative to other two, but this temperature increase (of $\sim 1^\circ\text{C}$) is not likely to be significant in practice. From these results, it is reasonable to suggest that even large changes in the resistivity of material close to the weld line will not affect the operation temperature of the part in service. This is not surprising as these heat flux increases are only present over a very small volume, and the high resistivity regions are beside the high conductivity parent materials, which can then effectively act as heat sinks.

Conclusions

This report discussed the LFW of aluminium (AA 1050) to copper (C101). The results showed that:

1. Linear friction welding is a viable way of joining dissimilar metals.
 2. Welds with very good mechanical (tensile and bend) properties could be produced.
 3. Welds with very good electrical properties could be produced with little or no detectable increase in resistivity at the weld line. Modelling was used to show that a non-detectable increase in the resistivity of material close to the weld line would not have an impact on the weld when in operation.
- In order for LFW to be used in production for the joining of these materials, some further work will be necessary. A demonstration of the robustness of the process, both in terms of repeatability at the same set of parameters and tolerance to parameter changes, will be necessary. Some further properties of the welds, such as corrosion resistance, may also need to be characterised. These aspects were beyond the scope of this work, which was to demonstrate the feasibility of joining aluminium to copper by LFW.

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References

1. I. Bhamji, M. Preuss, P. L. Threadgill and A. C. Addison: 'Solid state joining of metals by linear friction welding: a literature review', *Mater. Sci. Technol.*, 2011, **27**, (1), 2–12.
2. I. Bhamji, A. C. Addison, M. Preuss and P. L. Threadgill: 'Linear friction welding', in 'Welding and joining of aerospace materials', (ed. M. C. Chaturvedi); 2011, Cambridge, Woodhead Publishing, 384–415.
3. Y. Miyajima, S.-Y. Komatsu, M. Mitsuhashi, S. Hata, H. Nakashima and N. Tsuji: 'Change in electrical resistivity of commercial purity aluminium severely plastic deformed', *Philos. Mag.*, 2010, **90**, (34), 4475–4488.
4. M. Braunovic and N. Alexandrov: 'Intermetallic compounds at aluminum-to-copper electrical interfaces – effect of temperature and electric-current', *IEEE Trans. Compon. Packag. Manuf. Technol. A*, 1994, **17A**, (1), 78–85.
5. Matweb: 'Oxygen-free electronic copper, UNS C10100', MC101A/10336, (viewed 13 July 2011).
6. Matweb: 'Aluminium 1050-H14', MA1050H14/8720, (viewed 13 July 2011).
7. P. Wanjara, E. Dalgaard, G. Trigo, C. Mandache, G. Comeau and J. J. Jonas: 'Linear friction welding of Al–Cu: Part 1 – process evaluation', *Can. Metall. Q.*, 2011, **50**, (4), 350–359.
8. E. Dalgaard, P. Wanjara, G. Trigo, M. Jahazi, G. Comeau and J. J. Jonas: 'Linear friction welding of Al–Cu: Part 2 – interfacial characteristics', *Can. Metall. Q.*, 2011, **50**, (4), 360–370.
9. E. D. Nicholas, T. Jessop and W. O. Dinsdale: 'Friction welding dissimilar metals', *Weld. Inst. Res. Bull.*, Sept. 1978, 271–276.
10. G. M. Workman and E. D. Nicholas: 'Friction welding aluminium and its alloys to various materials', *Met. Mater.*, 1986, **2**, (3), 138–140.
11. T. A. Mai and A. C. Spowage: 'Characterisation of dissimilar joints in laser welding of steel–kovar, copper–steel and copper–aluminium', *Mater. Sci. Eng. A: Struct. Mater. Prop. Microstruct. Process.*, 2004, **374**, (1–2), 224–233.
12. B. Gulenc: 'Investigation of interface properties and weldability of aluminum and copper plates by explosive welding method', *Mater. Des.*, 2008, **29**, (1), 275–278.
13. L. Lutterotti, S. Matthies, H. R. Wenk, A. S. Schultz and J. W. Richardson: 'Combined texture and structure analysis of deformed limestone from time-of-flight neutron diffraction spectra', *J. Appl. Phys.*, 1997, **81**, (2), 594–600.
14. Copper Development Association: 'Pub 22 – copper for busbars', 1996, <http://www.copperinfo.co.uk/busbars/pub22-copper-for-bus-bars/homepage.shtml>.
15. Copper Development Association: 'A6022 – application data sheet – ampacities and mechanical properties of rectangular copper bus bars', http://www.copper.org/publications/pub_list/pdf/a6022.pdf.
16. Y. Ocak, S. Aksöz, K. Keşlioğlu, N. Maraşlı, E. Çadırılı and H. Kaya: 'Interfacial energies of solid CuAl₂ in the CuAl₂–Ag₂Al pseudo binary alloy', *Thin Solid Films*, 2010, **518**, (15), 4322–4327.
17. S. N. Ojha, K. Chattopadhyay and P. Ramachandrarao: 'Microstructure and mechanical properties of Al–CuAl₂ eutectic alloys solidified over a heat pipe', *J. Mater. Sci.*, 1983, **18**, (4), 1174–1182.