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Influence of heat treatment on the properties of explosively welded Cu-Al joints
Wpływ obróbki cieplnej na właściwości złączy Cu-Al zgrzewanych wybuchowo

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Abstract: *Explosive welding of copper C10200 to aluminium alloy AW 5083 was performed. C10200 was proposed as a flyer plate due to its suitable plastic properties. A parallel layout of welded metals was selected to attain a more stable welding process. Welding parameters and conditions were determined. The surfaces of both materials were mechanically machined and degreased prior to welding which was performed using Semtex S30. The bimetals were characterized by a regular wavy interface. The aim of the research was to establish the influence of heat treatment on both the structure and microhardness at the interface of the explosively welded bimetal Al-Cu. Heat treatment was performed at 250, 300 and 350 °C over 2, 3 and 4 h. After heat treatment, an increase in Inter Metallic Compounds (IMC) was observed, proportional to the increasing temperature. An analysis of chemical composition carried out by EPMA (Electron Probe Micro Analysis) confirmed the presence of Inter Metallic Phases (IMP) such as θ (Al_2Cu), η_2 (Al_2Cu), ξ_2 (Al_3Cu_4), δ (Al_2Cu_3), γ_1 ($A1_4Cu_9$). The microhardness decreased after the heat treatment in the bimetal but significantly increased at the interface as a consequence of IMC formation.*

Streszczenie: *Wykonano zgrzewanie wybuchowe stopu aluminium miedź C10200 i AW 5083. C10200 został zaproponowany jako płyta napędzana ze względu na jego odpowiednie właściwości plastyczne. Wybrano równoległy układ zgrzewanych metali, aby uzyskać bardziej stabilny proces łączenia. Określono parametry i warunki łączenia. Powierzchnie obu materiałów zostały poddane obróbce mechanicznej i odtłuszczeniu przed zgrzewaniem wykonanym przy użyciu Semtex S30. Bimetale charakteryzowały się regularną falistą powierzchnią styku. Celem badań było określenie* *wpływu obróbki cieplnej zarówno na strukturę, jak i mikrotwardość na granicy faz bimetalu Al-Cu zgrzewanego wybuchowo. Obróbkę cieplną przeprowadzono w 250, 300 i 350 °C przez 2, 3 i 4 godziny. Po obróbce cieplnej zaobserwowano wzrost związków międzymetalicznych (IMC), który był proporcjonalny do wzrostu temperatury. Analiza składu chemicznego przeprowadzona przez EPMA (Electron Probe Micro Analysis) potwierdziła obecność IMP takich jak θ (Al_2Cu), η_2 (AlCu), ξ_2 (Al_3Cu_4), δ (Al_2Cu_3), γ_1 (Al_4Cu_9). Mikrotwardość zmniejszyła się po obróbce cieplnej w bimetalu, ale znacznie wzrosła na granicy faz w wyniku tworzenia IMC.*

Keywords: *explosive welding, detonation velocity, copper, aluminium alloy, intermetallic compounds, EDS analysis, microhardness*
Słowa kluczowe: *zgrzewanie wybuchowe, prędkość detonacji, miedź, stop aluminium, związki międzymetaliczne, analiza EDS, mikrotwardość*

1. Introduction

There are many solid state welding technologies such as diffusion, friction, ultrasonic etc. However, explosive welding can be considered to be the most suitable of the available technologies by which means two or more metals with different physico-chemical properties can be joined, besides which other methods do not bring the required results. Explosive welding is a solid-state process which produces a high velocity interaction of dissimilar metals by a controlled detonation. Oxides found on material surfaces must be removed by mechanical or chemical means. Surface atoms of the two metals must come into intimate contact to achieve a metallic bond. Fusion welding of dissimilar materials such as Al and Cu appears very interesting because of the high mismatch in physical properties, mutual solubility and formation of intermetallic compounds (IMCs) in the Cu-Al binary system. The reason for using Al-Cu bimetals in terminals of copper connecting conductors with aluminium conductors, terminal stirps switchgears, substation and switch-yard bimetallic clamps and connectors etc., is their high electrical, and thermal conductivity [1-3]. Therefore, Cu-Al bimetal was explosively welded and succesfully prepared as this preparation of the bimetal seemed to be the most effective and reliable. The formation of intermetallic phases (IMP) is not very desirable with regard to Al-Cu joint properties. The joint is harder but brittle. That is why the temperature range in which the components are to be used should be carefully chosen.

2. Experimental

2.1. Welded materials and welding specifications

1-mm thick Copper C10200 and 10-mm thick aluminium alloy AW 5083 were suggested as experimental materials for the explosive welding Figure 1 [1]. Copper was designed as the flyer plate and Al as the base plate. Nine samples were cut from the produced Cu-Al bimetal and were heat treated at 250, 300 and 350 °C over 2, 3 and 4 h (Table 1). Temperatures were selected from a review of the research carried out in this field as well as the aluminium – copper binary diagram. All samples were sealed and analysed using EPMA and EDS analysis. The final bimetal, as prepared, can be seen in Figure 2.

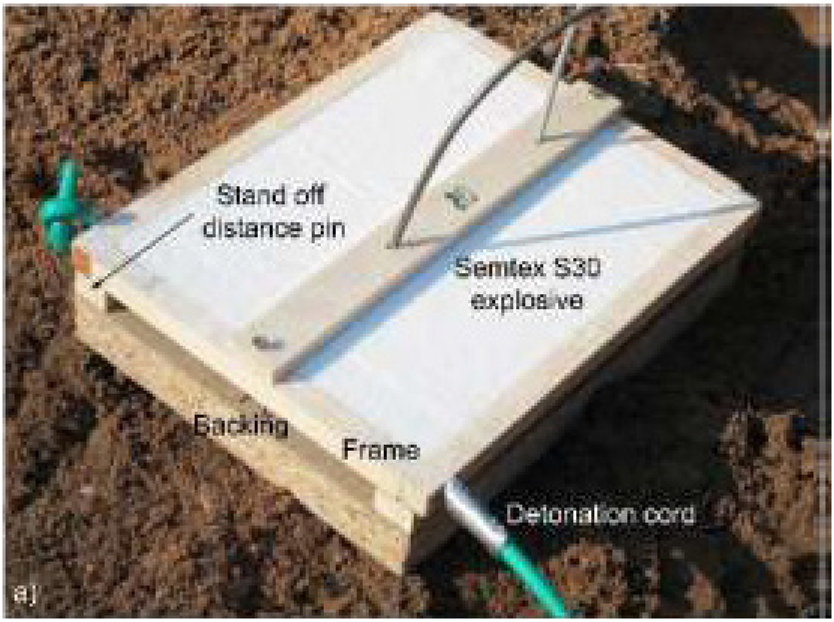

Figure 1. Experimental set-up

– dimensions of base plate (Al): 150×190 mm,
– dimensions of accelerated plate (Cu): 105×150 mm,
– Semtex S30, mass 247.1 g, density 1.09 g/cm^3,
– detonation fuse: Starline 12, detonation speed 6500 m/s,
– stand off distance: 2.0 mm.

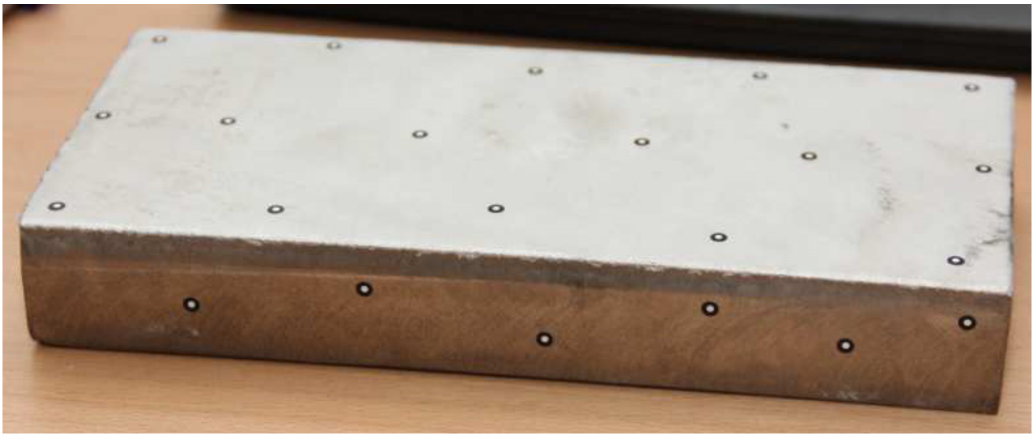

Figure 2. The final aluminium – copper bimetal

Table 1. Labeling of samples and the annealing process

Label	Temperature [°C]	Hold time [h]	Process of cooling
2502	250	2	Enclosed oven
2503	250	3	
2504	250	4	
3002	300	2	
3003	300	3	
3004	300	4	
3502	350	2	
3503	350	3	
3504	350	4	

2.2. Analytical methods

Analysis of the thickness of the IMCs present at the interfaces, elemental linescans and mapping, local chemical composition were carried out using a HITACHI SU 3500 electron microscope equippped with X-max 50 mm^2 Oxford Instruments detector for EDS analysis. Also, microhardness measurements were carried out but for brevity not all results are given.

3. Results

3.1. Microstructure analysis of bimetals

X-ray microanalysis was carried out on 9 samples, various points being chosen on each sample where qualitative and quantitative analysis, concentration linescans and mapping were performed. For the sake of simplicity and briefness only some pictures are shown (samples 2502 and 3004). Measurements were performed at different magnifications as the thickness of the joints was not constant along their cross-section. The aim of the X-ray analysis was to observe the concentration changes across the welded joint mainly in the mixed regions where the IMCs were supposed to originate. The interfaces of all joints were regular and wavy exhibiting a typical feature of explosively welded materials [5-7].

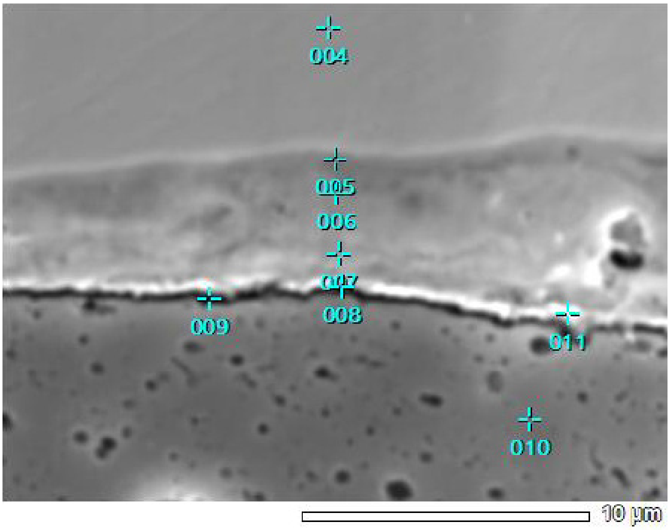

Figure 3. Point EDS analysis of sample 2502 – composition

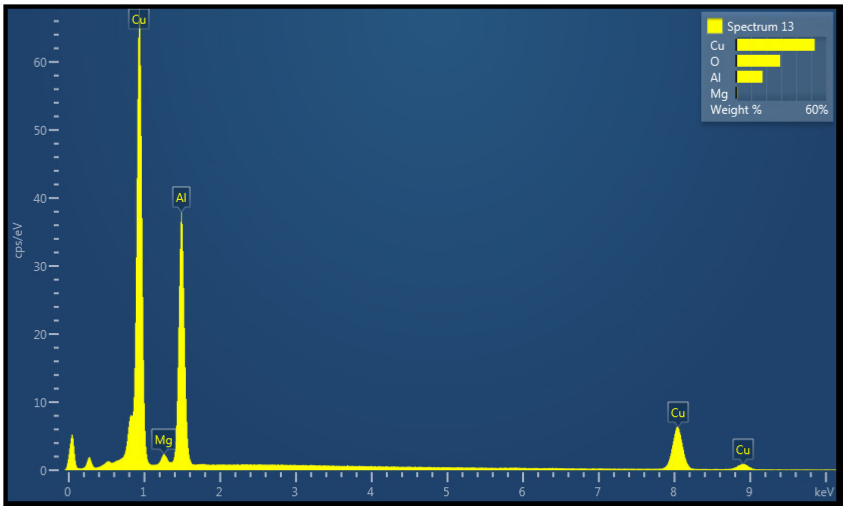

Figure 4. X-ray spectrum of sample 2502

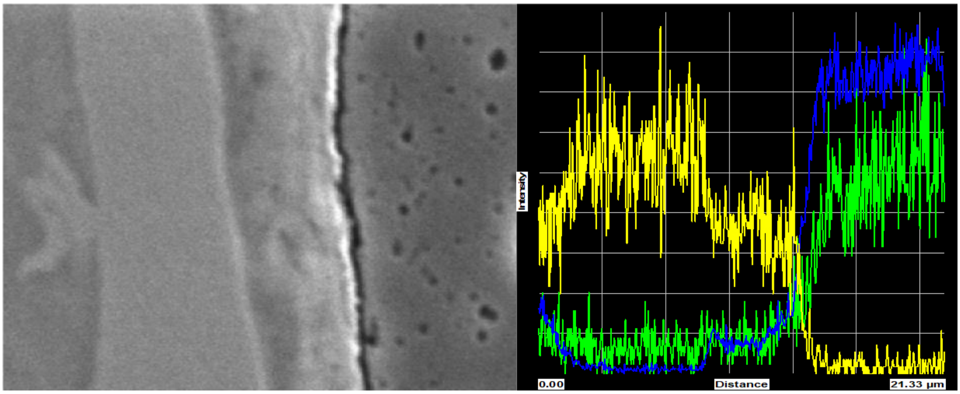

Figure 5. Concentration profiles of sample 2502 (Cu (in yelllow), Mg (in green), Al (in blue))

Table 2. Quantitative EDS analysis for sample 2502

Spot	Mg [at.%]	Al [at.%]	Cu [at.%]	IMC
004	0.62	10.82	88.56	–
005	0.12	1.25	98.63	–
006	0.03	1.24	98.73	–
007	–	28.60	71.40	–
008	0.93	33.39	65.68	γ_1 (Al_4Cu_9)
009	–	31.13	68.87	γ_1 (Al_4Cu_9)
010	8.71	91.29	–	–
011	–	37.53	62.47	δ (Al_2Cu_3)

Results of the quantitative analysis of the 2502 samples are given in Table 2, Figures 3-6 and those of 3004 are given in Table 3. As can be seen, novel IMCs were identified. In Figure 5, the concentration profile of sample 2502 is shown. In Figures 6 and 7, the elemental distribution of both samples can be seen. In Table 4, all intermetallic phases that were identified using EDS analysis, are given.

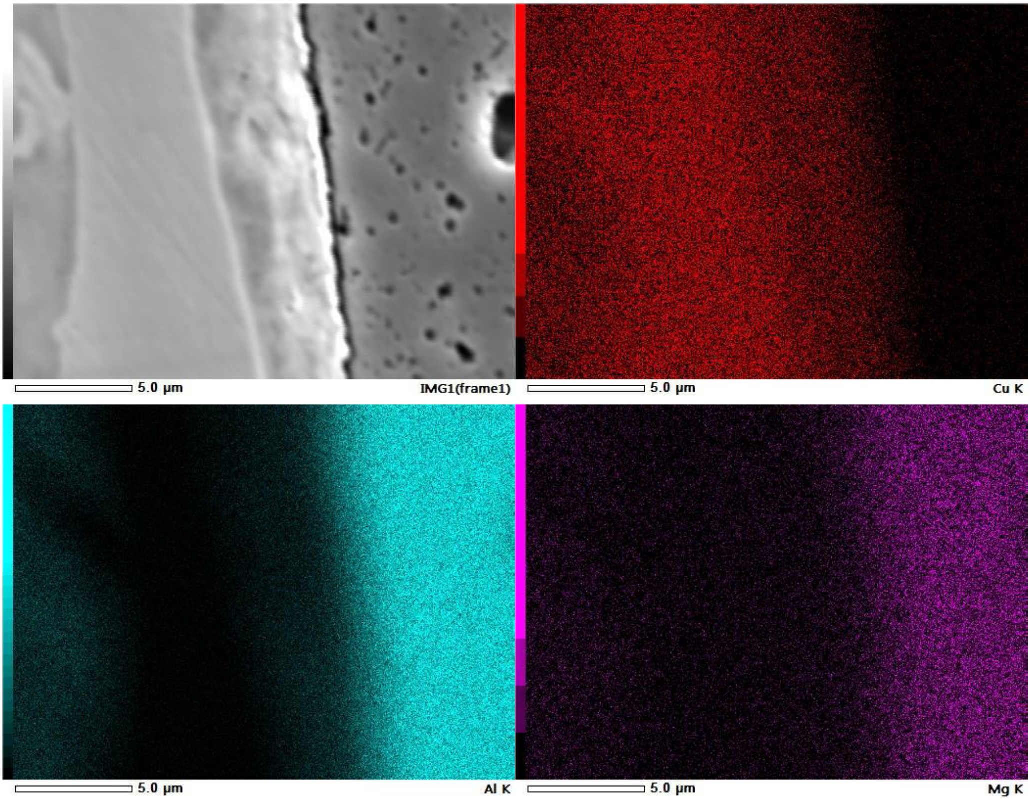

Figure 6. Elemental distribution – sample 2502

Table 3. Quantitative EDS analysis for sample 3004

Spot	Mg [at.%]	Al [at.%]	Cu [at.%]	IMC
004	0.007	1.18	88.56	–
005	1.64	37.50	60.85	δ (Al_2Cu_3)
006	0.57	42.83	56.60	ξ_2 (Al_3Cu_4)
007	1.17	48.87	49.96	η_2 (AlCu)
008	2.27	62.53	35.20	–
009	1.62	86.44	11.94	–
010	4.29	95.21	0.50	–

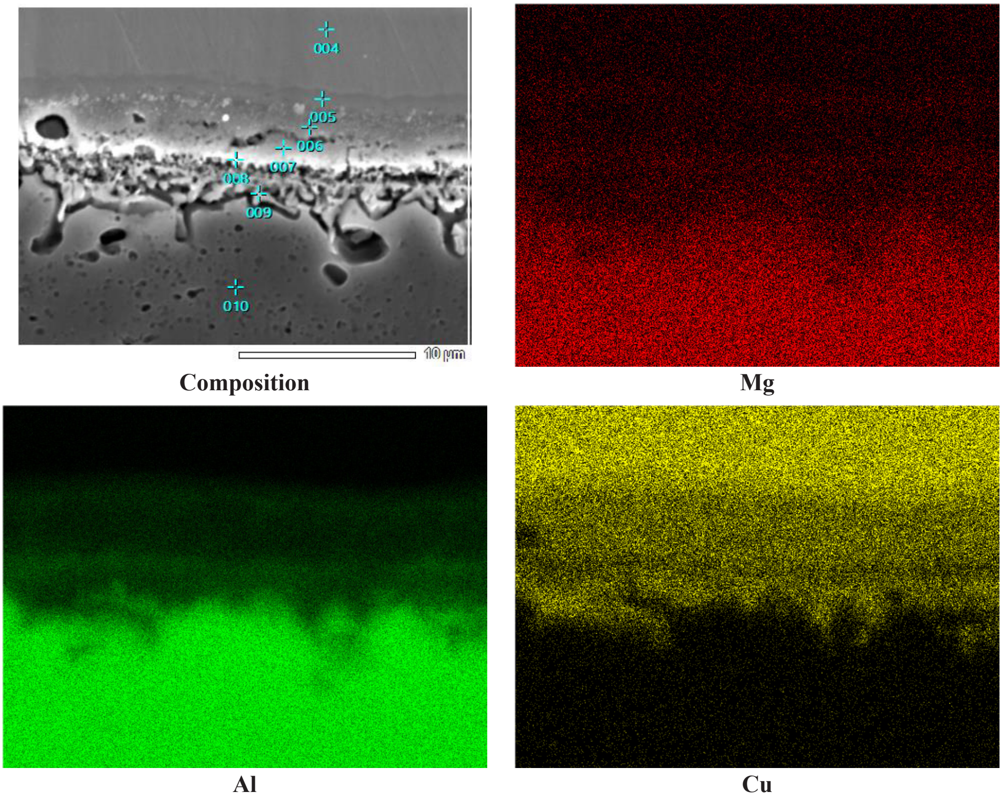

Figure 7. Elemental distribution – sample 3004

Table 4. The results of EDS analysis and all identified IMCs

Label	Temperature [°C]	Hold time [h]	Intermetallic phase
2502	250	2	δ ($A\ _2Cu_3$); γ_1(Al_4Cu_9)
2503	250	3	ϑ (Al_2Cu); δ (Al_2Cu_3)
2504	250	4	υ (Al_2Cu); η_2 (AlCu)
3002	300	2	η_2 (AlCu); δ (Al_2Cu_3)
3003	300	3	δ (Al_2Cu_3)
3004	300	4	η_2 (AlCu); ξ_2 (Al_3Cu_4); δ (Al_2Cu_3)
3502	350	2	η_2 (AlCu); ξ_2 (Al_3Cu_4)
3503	350	3	ξ_2 (Al_3Cu_4); δ (Al_2Cu_3)
3504	350	4	ξ_2 (Al_3Cu_4)

3.2. Microhardness measurements

The location of microhardness measurements across the welded bimetal interface is shown in Figure 8. An increase in microhardness observed at the interface, results from work hardening induced by the high velocity impact [4] and also by the presence of IMC. At a temperature of 250 °C over 2 h, the average microhardness at the interface was 236.5 $HV_{0.005}$, at a temperature of 250 °C over 3 h, 240 $HV_{0.005}$ and at 250 °C over 4 h, 231 $HV_{0.005}$.

Table 5. Microhardness measurement results for samples 2502, 2503, 2504

Distance [µm]	Sample 2502		Sample 2503		Sample 2504	
	Cu	Al	Cu	Al	Cu	Al
25	114	65	114	65	114	63
50	114	69	114	76	109	65
75	109	76	109	76	105	76
100	114	109	114	90	90	69
125	101	105	105	94	94	94
150	101	101	105	94	97	94
175	109	107	101	87	94	97
200	114	105	94	94	105	94
225	109	109	101	94	94	90
250	114	109	101	94	94	97
275	114	105	94	87	97	94
300	101	101	97	87	101	94
325	114	105	101	97	105	90
350	105	109	94	87	90	90
375	101	101	97	94	87	97
400	105	105	101	87	84	97
425	109	101	105	94	90	94
450	105	105	90	97	90	94
Interface Average $HV_{0.005}$	236.5	–	240	–	231	–

Figure 8. Plane of microhardness measurement across interface

The plane of microhardness across the copper –aluminium alloy AW5083 bimetal, annealed at 250 °C, is given in Figure 9. The influence of annealing times on microhardness was observed. The longer annealing times resulted in a decrease of the mean microhardness of the flyer plate and the base material. The mean microhardness of copper and aluminium alloy AW5083 after annealing for 2 h, was 109 and 99 $HV_{0.005}$, respectively. Increasing the annealing time to 3 h resulted in a drop of mean microhardness of the welded materials. The microhardness of copper decreased to 102 $HV_{0.005}$ whereas that of aluminium alloy decreased to 89 HV0.005. After annealing the bimetal for 4 h, the microhardness of copper dropped to 97 $HV_{0.005}$ whereas that of aluminium alloy AW5083 decreased to 88 $HV_{0.005}$.

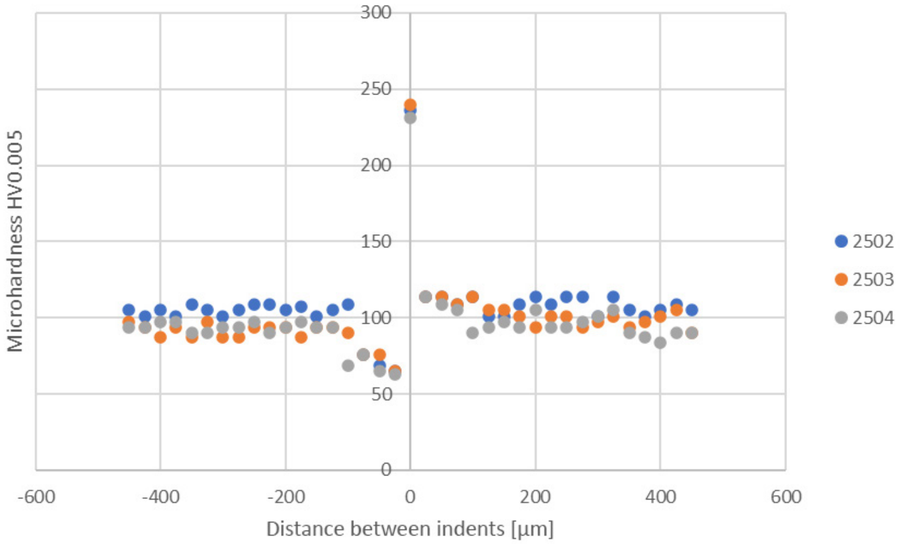

Figure 9. The course of microhardness across AW5083 – copper bimetal annealed at 250 °C for 2, 3, and 4 h

4. Conclusions

- The annealing process of bimetal resulted in thickness increase at the welded interface. At 250 °C with 2 h. hold time, it was 0.67 µm, that at 3 h. hold time, 0.81 µm, and finally at 4 h., 1.04 µm. At 300 °C, with a 2 h. hold time it was 1.41 µm, 3 h. hold time 1.78 µm and finally at 4 h. hold time 2.01 µm. At 350 °C 2 h. hold time 4.37 µm, 3 h. hold time 5.11 µm and 4 h. hold time 5.86 µm.
- Using EDS analysis, the heterogeneity of the welded joints was investigated. The annealing process resulted in the formation of IMCs. During annealing, the IMC layer growth process occurs via atom diffusion at elevated temperatures [9]. The formation of IMC depends on both the annealing temperature and the hold time. The following IMCs were identified: υ (Al_2Cu), η_2 (AlCu), ζ_2 (Al_3Cu_4), δ (Al_2Cu_3), γ_1 (Al_4Cu_9)
- The microhardness measurements confirmed the effect of softening which at a temperature of 250 °C for all hold times on the Al side ranged up to 75-100 µm with 92 $HV_{0.005}$. The average microhardness of Cu was 102 $HV_{0.005}$. In the welded interface the average microhardness was 236 $HV_{0.005}$.
- A temperature of 300 °C for all hold times caused considerable softening of both materials away from the welded interface up to 525 µm. The average microhardness of Al = 80 $HV_{0.005}$, that of Cu = 83 $HV_{0.005}$ and that of the welded interface = 236 $HV_{0.005}$. A temperature of 350 °C for all hold times caused the most considerable softening of both materials with average microhardness of Al = 75 $HV_{0.005}$, Cu = 72 $HV_{0.005}$ and that of the welded interface, 255 $HV_{0.005}$.

- ♦ Increasing the temperature and hold time resulted in increases in the microhardness on account of a lowering of the mechanical properties of Al and Cu (ductility, tensile strength).
- ♦ The formation of intermetallic phases in the region of the weld, resulted in an increase in microhardness. Interface layers of greater thickness are sites for initiation and propagation of cracking, resulting in a decrease in interface strength.

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