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Solid state diffusion welding of Cu-Fe/Al/Ag and Al-Ni dissimilar metals

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Diffusion Bonding is a solid state welding technology which allows joining of similar or different materials: metal-metal, metal-ceramics, ceramics-ceramics etc. A major advantage of this method is new developments of bimetals or dissimilar material couples. Many applications and emerging applications are dependent on dissimilar material joints. This paper presents the research results on diffusion bonding of Cu-Fe, Cu-Ag, Cu-Al and Al-Ni dissimilar metallic couples which could be used in electrotechnical or electrical industries. The obtained jonctions are characterized at the interface from the point of view of microstructural characteristics, X-ray diffraction, mechanical and electrical properties. The optimum technological parameters (temperature, time, pressure, atmosphere etc.) are also specified.

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Keywords: Diffusion welding, Solid state diffusion, Diffusion bonding

1. Introduction

Diffusion bonding is a special solid state welding method which can be used to join dissimilar materials. To differentiate this method from other joining technologies such as deformation bonding or transient liquid phase joining, diffusion welding can be defined as a process that produce solid state coalescence between two materials under the following conditions [1]:

- joining occurs at a temperature below the melting point, T_m, of the materials to be joined (usually > 1/2 T_m);
- coalescence of contacting surfaces is produced with pressures below those that would cause macroscopic deformation to the part;
- a bonding aid can be used, such as an interface foil or coating, to either facilitate bonding or prevent the creation of brittle phases between dissimilar materials, but the material should not produce a low temperature liquid eutectic upon reaction with the materials to be joined.

This solid state welding process occurs into both materials being bonded by thermal activate diffusion mechanisms with the result of a diffusion area which defines the bond's strength. In the first stage of diffusion bonding process, the deformation of surface asperities takes place by plastic flow and creep. The second stage consists in the grain boundary diffusion of atoms to the voids and grain boundary migration while in the third stage, the volume diffusion of atoms to the voids is produced. The diffusion welding process, that is, the application of pressure and temperature to an interface for a prescribed period of time, is generally considered complete when cavities fully close at the faying surfaces.

The diffusion bonding of material combinations depends on a lot of influencing factors [2]: process parameters (pressure, temperature, time and atmosphere), surface conditions (cleaning process, topography), heat input (thermal activation), component geometry and absence or presence of the intermediate layers.

In this moment, there are few studies referring to the welding of binary metals couples [3, 4], in compare with those regarding to dissimilar alloys welding [5, 6]. The experimental data resulted from welding couples of dissimilar binary metals is useful to facilitate the thermodynamic analysis of the systems to be compared to the data resulted from mathematical modeling.

In this paper, the researches results of some dissimilar metallic couples (Cu-Fe, Cu-Ag, Cu-Al and Al-Ni) obtained by diffusion welding method, with potential applications in the electrotehnical industry, electronics or electrical industries are presented.

2. Experimental procedure

In order to realize dissimilar metallic bonding of Cu-Fe, Cu-Ag, Cu-Al and Al-Ni by diffusion welding procedure, the following metals have been selected:

- electrolytic Cu plates of 99,9% purity;
- Al plates of 98,724 % purity;
- electrolytic Ni plates of 99,97% purity;
- Fe plates of ARMCO type with C under 0, 02%.
- Ag plates of 99, 9% purity.

The chemical compositions of Al and Ni metals are presented in Table 1 and Table 2. Electrolytic Ni plates were reduced by cold plastic deformation from the thickness of 5 mm to the thickness of 3.5 mm and they were annealed in NH_3 atmosphere in order to eliminate the hardening induced by cold lamination.

Table 1. Chemical composition of Al (at %) – 6060 type.

Mn	Si	Cr	Cu	Ti	Fe	Zn	Mg	Al
0.03	0.463	0.011	0.034	0.012	0.219	0.047	0.46	remainder

Table 2. Chemical composition of Ni (at %) - 28102 type.

C	Cu	P	S	Co	Fe	Pb	Zn	Ni
0.005	0.001	0.0002	0.0005	0.0003	0.003	0.0001	0.0005	remainder

After annealing, the faying surfaces of Ni plates were cleaned and superficial activated by polishing and grinding on metallographic paper.

The thicknesses of the plates subjected to the bonding experiments were the following:

- for Cu-Fe jonction: Cu (85 x 20 x 5) mm; Fe (88 x 20 x 11) mm;
- for Cu-Ag jonction: Cu: (42/90 x 20 x 5) mm; Ag: (35/75 x 10 x 0,5) mm;
- for Cu-Al jonction: Cu: (47/58 x 20 x 5) mm; Al: (52/60 x 30 x5) mm;
- for Ni-Al jonction: Ni: (32/39 x 33 x 3,5) mm; Al: (29/39 x 30 x 5) mm

Before diffusion welding, the faying surfaces of metallic plates were superficial activated by polishing on the silicon metallographic paper. The planed and cleaned surfaces of the materials were brought into close contact by pressing with 200 kg f/cm^2 at a manual press.

The diffusion bonding experiments of Cu-Fe, Cu-Ag, Cu-Al and Al-Ni metallic couples took place in a furnace of SAFED type with a continuous band, in NH$_3$ cracked atmosphere. In order to assure a minimal pressure at the material interface, the heavier plates were set on the lighter ones and having lower melting points (i. e. Fe plates over the Cu plates, Cu plates over the Ag plates) and they were put in a graphite tray on the furnace band.

The optimum diffusion welding technological parameters used to obtain good jonctions of Cu-Fe, Cu-Ag, Cu-Al and Al-Ni dissimilar metallic couples are presented in Table 3.

Table 3. The optimum diffusion welding parameters of the experimented metallic couples.

Metallic couples	Furnace temp. zone 1 (^{0}C)	Furnace temp. zone 2 (^{0}C)	Furnace temp. zones 3, 4 and 5 (Diffusion bonding treatment temperature) (^{0}C)	Speed band of the furnace (mm/min)	Maintaining time on the furnace band in the zones: 3, 4 and 5 (min)
Cu-Fe	650	700	1100 ± 10	max.180	10 ± 2
Cu-Ag	650	650	800 ± 10	max.180	10 ± 2
Al-Cu	500	500	640 - 650	max.180	8 ± 2
Al-Ni	500	500	660 - 670	max. 90	16 ± 2

3. Results and discussions

Specimens were sampling from the Cu-Fe, Cu-Ag, Al-Cu and Al-Ni diffusion welded components in order to examine the interface zones by optical microscopy, mechanical and electrical properties.

Interface analysis of the Cu-Fe, Cu-Ag, Al-Cu and Al-Ni diffusion welded specimens was observed with an optical microscope of Carrziess type with an Axiovision software included.

In Figs. 1 and 2, the optical microscopy images of Cu-Fe and Cu-Ag jonctions obtained by diffusion bonding at 1100^{o}C and 807^{o}C respectively, are presented.

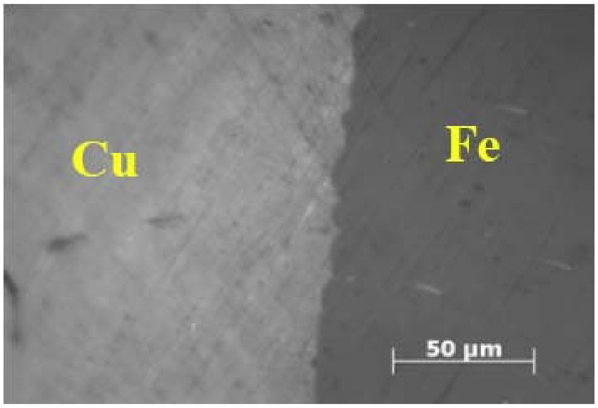

Fig.1. Optical microscopy image of Cu-Fe specimen at the interface, transverse section, x 500.

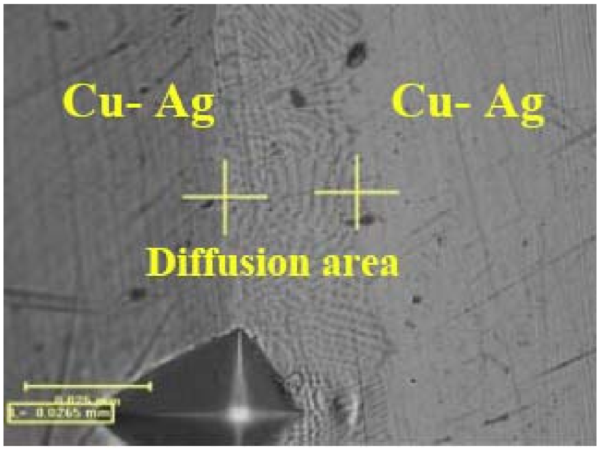

Fig.2. Optical microscopy image of Cu-Ag specimen at the interface, transverse section, x 500.

From the phase diagram of the Fe-Cu system [7], Fe and Cu present a very low solubility, practically being immiscible, and each metal crystallizing in a very well defined crystallographic lattice: CVC (Fe) and CFC (Cu). The welding at the Cu-Fe interface is realized by diffusion processes, plastic flow and creep, at micro level (fig. 1). For the Cu-Ag diffusion bonded metallic couple, there is a diffusion area of 216.2 μm formed at the interface which consists of an eutectic alloy made up from solid solution crystals: α (CFC) + β (CFC), fig. 2.

The optical microscopy images of Ni-Al and Cu-Al interface jonctions are presented in figs. 3 and 4, respectively. The microstructure analysis have showed the existence of a very narrow diffusion area of about 0.3÷0.6μm for both Ni-Al and Al-Cu interface couples.

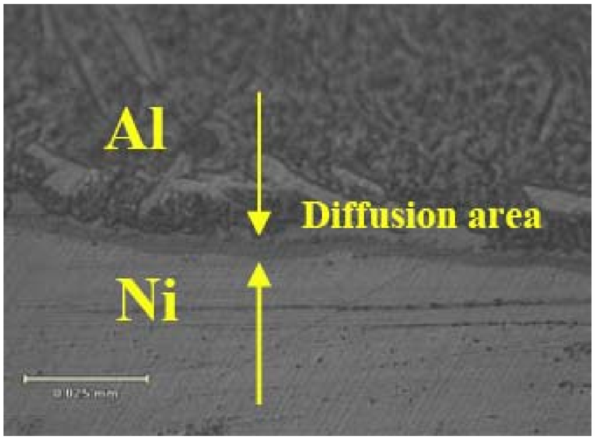

Fig.3. Optical microscopy image of Al-Ni specimen at the interface, transverse section, x 500.

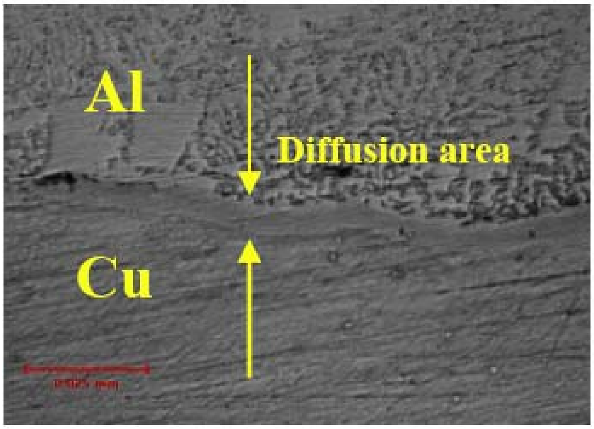

Fig.4. Optical microscopy image of Al - Cu specimen at the interface, transverse section, x 500.

For Ni-Al and Cu-Al dissimilar metallic couples, the presence of compounds with hexagonal structure of Al_3Ni_2 type (fig. 5) and tetragonal and cubic structures (Al_2Cu and Al_4Cu_9 types, respectively), fig. 6, were evidenced by X-ray diffractions and Rietvelt diagrams.

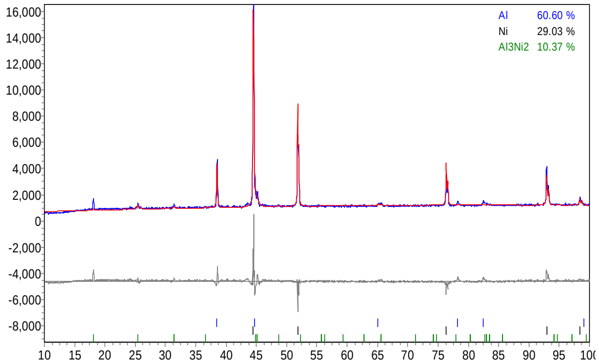

Fig.5. Rietvelt diagram with quantitative evidence of the Al_3Ni_2 compounds existing at the Al-Ni interface.

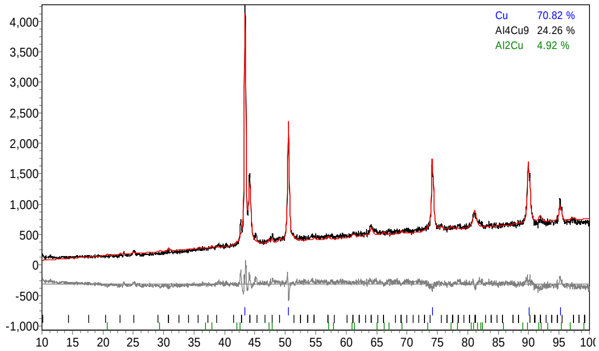

Fig.6. Rietvelt diagram with quantitative evidence of the Al_4Cu_9 and Al_2Cu compounds existing at the Al-Cu interface.

Vickers microhardness measurements were carried out on the Cu-Fe, Cu-Ag, Al-Cu and Al-Ni diffusion welded specimens with a microhardness device of EM 700 type. The Vickers microhardness values for Cu-Fe and Ag-Cu diffusion bonded components are presented in figs. 7 and 8, respectively.

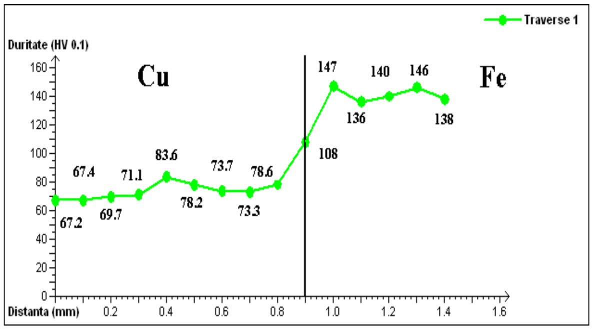

Fig.7. Vickers microhardness values ($HV_{0.1}$) measured on the Cu matrix, Cu-Fe interface and Fe matrix.

The microhardness value measured on the Cu-Fe interface (108 $HV_{0.1}$) have shown an increasing with 34 $HV_{0.1}$ in compare with the microhardness medium value registered on the Cu matrix (74 $HV_{0.1}$) and a decreasing with 33 $HV_{0.1}$ in compare with the medium value obtained on the Fe matrix (141 $HV_{0.1}$), fig. 7.

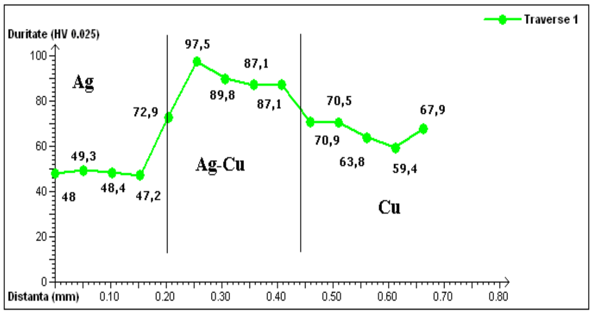

Fig.8. Vickers microhardness values ($HV_{0.025}$) measured on the Ag matrix, Ag-Cu interface and Cu matrix.

From the Vickers microhardnes values analysis, fig. 8, it is shown an increasing of microhardness values at the interface with about 40 HV in compare with the microhardness values obtained on the Ag matrix and with about 20 HV in compare with those registered on the Cu matrix. The highest microhardness values are registered on the interface zone of the Cu-Ag jonction because of the eutectic structure alloy composed of α and β solid solution crystals with CFC crystallographic lattices.

In figs. 9 and 10, the Vickers microhardness values for Ni-Al and Cu-Al joints are presented.

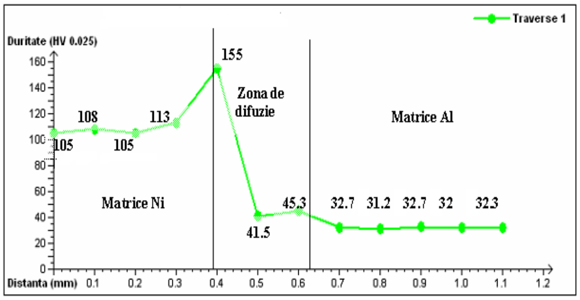

Fig.9. Vickers microhardness values (HV 0,025) measured on the Al matrix, Ni-Al interface and Ni matrix.

From the micrographic examination of the Al-Ni diffusion bonded samples is found out the existence of about 0.3µm diffusion zone and the intermetallic compounds presence near to the Al matrix, fig 3, x 500. The existence of the hard compounds with hexagonal structure of Al_3Ni_2 type, have confirmed high microhardness values at the interface (155 HV), fig. 9.

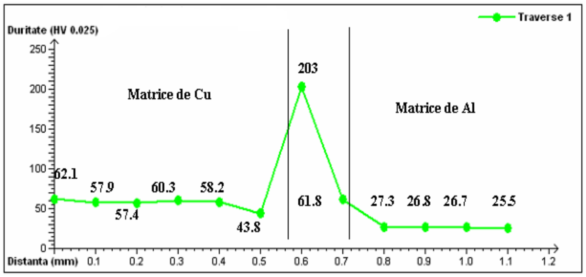

Fig.10. Vickers microhardness values (HV 0,025) measured on the Cu matrix, Cu-Al interface and Al matrix.

From the interface micrographic examination of Cu-Al diffusion bonded samples is found out the existence of about 0.6µm diffusion zone and the intermetallic compounds presence near to Al matrix. Increasing of the microhardness values (203 HV), fig. 10, is owing to the existence of hard compounds with tetragonal structure of Al_2Cu type and with cubic structure of Al_4Cu_9 type at the Cu-Al interface, figs. 4 and 6.

The resistivity and electrical conductivity tests were realized with the Four- Point Method by TESLA BM 395 bridge. The measurements results are presented in Table 4. The obtained results have shown that the electrical properties for studied dissimilar metallic couples are included in the interval of the electrical conductivity (10^5 and 10^8 Ω^{-1}x cm^{-1}) and electrical resistivity (10^{-5} and 10^{-8} Ω x cm), specific to the metallic materials [8].

Table 4. Resistivity and electrical conductivity values of each metal and joints obtained by diffusion welding method.

No crt.	Material	Electrical characteristics	
		Electrical Resistivity (Ω x cm)	Electrical Conductivity (Ω^{-1} x cm^{-1})
1	Cu	0.034 x10^{-5}	29 x 10^{5}
2	Fe	32.54 x 10^{-5}	0.031 x 10^{5}
3	Ag	0.36 x 10^{-5}	2.8 x 10^{5}
4	Al	0.03 x 10^{-5}	33.3 x 10^{5}
5	Ni	0.046 x 10^{-5}	21.7 x 10^{5}
6	Cu-Fe	33.37 x 10^{-5}	0.030 x 10^{5}
7	Cu-Ag	2.71 x 10^{-5}	0.37 x 10^{5}
8	Al-Ni	0.564 x 10^{-5}	1.77 x 10^{5}
9	Al-Cu	13.6 x 10^{-5}	0.073 x 10^{5}

4. Conclusions

The optimum technological parameters for obtaining of dissimilar metallic jonctions are the following:

✓bonding temperatures (^{0}C): 1100 ± 10 (Cu-Fe), 800 ± 10 (Cu-Ag), 640 – 650 (Al-Cu), 660 – 670 (Al-Ni);

✓furnace band speed (mm/min): max.180 (Cu-Fe, Cu-Ag and Al-Cu) and max. 90 (Al-Ni);

✓maintaining time on the furnace band (min): 10 ± 2 (Cu-Fe and Cu-Ag), 8 ± 2 (Al-Cu), 16 ± 2 (Al-Ni);

✓working atmosphere: cracked NH_3;

Microstructural analyses have shown the existence of a diffusion area for Cu-Ag metallic couple with α and β solid solution crystals. For Cu-Al and Ni-Al metallic couples, the presence of some intermetallic compounds such as Al_2Cu and Al_4Cu_9 and, Al_3Ni_2 respectively, in the interface zones are evidenced.

Electrical properties measurements have shown electrical properties for the studied couples with specific values to the compact metallic materials. These jonctions can be used in the electrical or electrotehnical field (i. e. Cu-Fe would be used in condition of existence of the electromotors forces, when improved mechanical properties of Cu and its consumption reduction are necessary; Cu-Ag jonction can be used in the electrical industry as electrical contacts and Cu-Al joints could be used in order to assure optimal electrical contact between the generator Cu bornes and Al bars for turbines).

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